Long-Term Bluff Recession Rates in Puget Sound: Implications for the Prioritization and Design of Restoration Projects

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COASTAL GEOLOGIC SERVICES

ESTUARY & SALMON RESTORATION PROGRAM

Table of Contents

Table of Tables

Table of Figures

Executive Summary

This report details the methods, analysis, and results of the *Long-Term Bluff Recession Rates in Puget Sound* project. This project was funded by the Washington Department of Fish and Wildlife (WDFW) Estuary and Salmon Restoration Program (ESRP) — Learning Program. The project benefited from technical guidance provided by: Tish Conway-Cranos, Nearshore Science Manager with WDFW ESRP; Hugh Shipman, Coastal Geologist with Washington Department of Ecology; and Ian Miller, Coastal Hazard Specialist with Washington Sea Grant.

Coastal bluffs are the most prevalent coastal landform type in the Puget Sound region, accounting for over 1,000 miles (or 42.6% by length) of the region's shore. Coastal bluff recession supplies the majority of sediment to Puget Sound beaches, which provide and maintain essential nearshore habitats for salmon, shellfish, and other fish and wildlife (Finlayson, 2006; Johannessen and MacLennan, 2007; Keuler, 1988). Little research has documented the range of bluff recession rates in the Puget Sound region (less than 25 published sites; Shipman 2004, 1995) or how those rates reflect changes in bluff morphology, geology, stratigraphy, or wave exposure.

The objective of this project was to increase understanding of the range and dominant drivers of long-term coastal bluff recession rates throughout the Puget Sound region by examining bluff recession at the regional scale and under a wide variety of conditions (see Figure 1 for geographic context). This study pairs the compilation of existing and new historical coastal bluff recession rates with a statistical analysis to explore the relative strength of different shore characteristics that are likely to influence long-term bluff recession. Most of the variables explored in this study have been mentioned or documented in the scientific literature on coastal bluffs, but have not been analyzed in detail in the Puget Sound region (Bray and Hooke, 1997; Emery and Kuhn, 1982; Rosen, 1977; Shipman, 2004).

This study was designed to explore as many potential drivers of bluff recession as data availability and appropriateness for a regional-scale analysis permitted. Bluff recession in the region is affected by multiple processes including wave attack, mass wasting events (landslides), and surficial erosion processes (Emery and Kuhn, 1982; Johannessen and MacLennan, 2007; Shipman, 2004). The variables explored in this study include: bluff height, bluff surface geology, bluff toe geology, maximum fetch, shore orientation, geomorphic shoretype, beach substrate, tidal range, latitude, permeable over impermeable bluff stratigraphy, location within the drift cell (percent down-drift of the littoral drift cell origin), and relative sea level change rates.

The dataset includes 185 long-term bluff recession rates from throughout the region that were measured across many years, ranging from 23 to 101 years (Figure 2, Map Figures). Recession rates were measured using two different approaches: historical air photo analysis in GIS and field-based measurements using US Coast and Geodetic Survey monuments. In total, 106 bluff recession measurements were made using aerial photo methods and 79 bluff recession measurements were made using field-based methods. Supporting data were compiled for all bluff recession rates for use in the statistical analysis. Recession rates, measurement locations, measurement methods, and all supporting data are included in the attribute table of the project geodatabase.

Long-term bluff recession rates were reported as end point rates (EPR, the total measured distance between the oldest and most recent yeas divided by the number of years between measurements) and in FT/YR. The average long-term erosion rate was -0.29 FT/YR (all erosion rates are given as negative numbers), which varied on average by 0.21 FT/YR across the bluffs sampled. The mean effective fetch measure was 10 miles (SD=12.30), and ranged up to a maximum of 61 miles. The variation in tidal range was relatively small (SD=2.40 FT) with a mean of 10.58 FT. The average bluff measured 89.45 FT in height, ranging from 10 to 360 feet (SD=77.39 FT). On average, recession rates were measured from bluffs that were located 57 percent of the drift cell length down drift from the cell origin (SD=0.29).

Of all the variables evaluated, measured fetch exhibited the strongest overall correlation with EPR (r^2=-0.43), which is negative and moderate in strength. Correspondingly, this measure also singularly explains the greatest proportion of variance in EPR of any of the continuous measurements (r^2=0.184). Tidal range had a positive and weak-to-moderate correlation with EPR (r^2=0.29) while the natural log-transformed bluff height had a negative and weak correlation with EPR (r=^{2}-0.24). There was a negative and weak linear association between drift cell percent down drift and EPR. Vertical Land Movement (VLM) had a very weak correlation with EPR (r^2=-0.09) and the slope with EPR was not statistically significant. For the categorical variables, only shoretype (r^2=0.133) and bluff feature (r^2=0.205) explain any meaningful variance in EPR (Table 7). In summary, the strongest documented drivers of bluff recession were fetch and tidal range. Weaker relationships with other variables were also documented however, they were not potentially causative or relatively weak in strength. The maximum fetch distance directly relates to the rate of bluff recession. Bluffs with greater tidal range recede at a slower pace than those with a narrower range of the tide.

The preferred statistical model includes the five variables that had the strongest relationships with bluff recession rates: fetch, tidal range, shoretype, surface geology, and measurement feature. Together these variables explain 41.5% of the overall variation in EPR. The combination of variables included in the preferred model reduces the mean residual errors of EPR to 0.161 FT/YR. Again, fetch and tidal range have the most direct effect on bluff recession rates, when compared to other variables explored in this study.

The model outputs are indicative of (historical) long-term bluff recession rates, and are not necessarily applicable to predictions of future bluff recession rates. They do not, for example, account for changes in sea level associated with climate change. Bluff recession rates are expected to accelerate in the future (Bray and Hooke, 1997). Model outputs can be viewed as a quantitative starting point for estimated rate of bluff recession at a given location, in the absence of measurement data.

There is inherent uncertainty and bias embedded in the erosion rates measured in this study that potentially skew the data towards the higher end of the range of erosion rates actually occurring in the Puget Sound region. Biases were associated with the selection of measurement locations, the data referenced in the stratification structure, and the locations of the NGS monuments.

This database represents a robust foundation that can be built upon in several different ways. Additional long-term bluff recession measure locations and rates could be incorporated into the dataset to augment the existing rates and address spatial gaps in coverage. Decadal-scale trends could be explored by conducting additional measurements from a subset of sites using aerial photography from the 1980s, 1990s, and 2000s and paired with higher resolution data such as storm events, geology, wave data, beach topography, substrate, and sediment transport rates. Additional research on the rate at which armored bluffs erode, as compared to unarmored bluffs, could provide valuable insight into the degree to which armor slows bluff recession.

Greater understanding of the rates and drivers of shore change in the Puget Sound region can inform better management, which can improve conditions for nearshore habitats, processes and the larger nearshore ecosystem as a whole. It can also be used to characterize the degree to which bluff erosion is likely to accelerate due to climate change. The greater the understanding of past trends, and the most relevant drivers of recession, the more easily we can identify which bluffs will be more vulnerable to accelerated bluff recession in the future. Bluff recession rates and the variables of greatest influence to those rates (e.g. fetch and tidal range) can be valuable when exploring restoration feasibility, particularly where and when infrastructure may become threatened. All of this enables improved management and preservation of coastal ecosystem processes, habitats, and the many other qualities for which the Puget Sound region is so valued.

Introduction

Puget Sound coastal bluffs are the most prevalent landform type in the region, accounting for over 1,000 miles (or 42.6% by length) of the region's shore. Coastal bluff recession provides critical sediment supply to Puget Sound beaches, which provide and maintain essential nearshore habitats for salmon, shellfish, and other fish and wildlife (Finlayson, 2006; Johannessen and MacLennan, 2007; Keuler, 1988). The Puget Sound region has a complex, crenulated shore with substantial variability in bluff characteristics (Shipman, 2004, Figure 1).

Figure 1. Location and configuration of the Puget Sound region in the northwest corner of Washington State.

Very little research has documented the range of bluff recession rates in the Puget Sound region(less than 25 published sites; Shipman 2004, 1995) or how those rates reflect changes in bluff form, geology, stratigraphy, or wave exposure. Existing bluff recession rates were measured from the Port Townsend (30 by 60 minute) quadrangle (Keuler, 1988), which included bluffs found along the shores of the Strait of Juan de Fuca, Rosario Strait, and Admiralty Inlet. These represent some of the most exposed bluffs in the region that are likely to be receding at a faster pace than more sheltered shores. No bluff recession rate measurements existed from the more sheltered bluffs in central and southern Puget Sound, making comparison of recession rates throughout the region not possible. There is a broad range of wave exposures along the bluffs of Puget Sound, though much of the region's bluffs are found in areas with less exposure than in the Port Townsend (30 by 60 minute) quadrangle. These less exposed bluffs make up the majority of bluffs in the region and are likely eroding at considerably slower rates.

Coastal bluffs in the Puget Sound region are valued for residential development. Regulations from Shoreline Master Programs and Critical Areas Ordinances determine how far a home is required to be "setback" from the crest of the bluff for new construction. The required setback distances vary across jurisdictions and there is little data to support their determination. Additionally, many homes were constructed and parcels platted prior to current regulations; these improvements often have smaller setback distances than what is allowable today.

Regional survey data has shown that coastal erosion is the most common concern of bluff property owners (Colehour + Cohen et al., 2014). A common disconnect has been documented among coastal property owners between the perceived and actual need for shore protection (armor) due to coastal erosion, i.e., coastal property owners tend to believe that their bluffs are receding at a more rapid pace than is actually occurring. As a consequence, many property owners feel compelled to protect their investment by armoring their bluffs, resulting in the disruption of sediment processes with forthcoming impacts to beach width, riparian vegetation, accumulation of large wood and beach wrack, fish and wildlife habitats, and invertebrate populations (Dethier et al., 2016; Heerhartz et al., 2014).

A better understanding of the range of bluff erosion rates can be used to inform land use decisions such as setback distances and regulations designed to limit the construction of shore armor, or to assess permit applications and geotechnical reports. Currently, Puget Sound Feeder Bluff Mapping has been used in the development of shoreline designation and associated regulations (MacLennan et al. 2013). Pairing actual bluff recession measurements with the qualitative mapping can further justify those regulations. Understanding bluff recession rates can also aid in the development of capital projects that aim to restore and protect beach systems. Regional bluff erosion rates have been used by CGS to assess the benefit and feasibility of sediment supply restoration sites in several counties in the Puget Sound region and sea level rise vulnerability in San Juan County (Coastal Geologic Services, 2013). Bluff recession rates have also been used to estimate the future volume of restored sediment input derived from the restoration of a bluff. Better information on the regional variability of bluff recession rates offers many utilities and opportunities to improve coastal management in the Puget Sound region.

Objectives

The objective of this project was to investigate the range and dominant drivers of long-term coastal bluff recession rates throughout the Puget Sound region. This study pairs the compilation of existing and new historical coastal bluff recession rates with a statistical analysis to explore the relative strength of different variables that are likely to influence long-term bluff recession (Bray and Hooke, 1997; Emery and Kuhn, 1982; Rosen, 1977; Shipman, 2004).

This study was designed to explore as many potential drivers of Puget Sound bluff recession as data availability and scale permitted. More controlling factors and processes are at work along the Puget Sound region's bluffs that could not be included in this analysis largely due to data shortcomings.

Lessons learned from this study can be used to inform further research, coastal management, regulations, and restoration, and ultimately preserve feeder bluff function in the Puget Sound region.

Methods

Overview

The objective of this study was to investigate bluff recession rates throughout the Puget Sound region and to explore the relative influence of different variables that drive blue erosion at the regional scale. Bluff recession in the region is caused by multiple processes including wave attack, mass wasting events (landslides), and surficial erosion processes (Emery and Kuhn, 1982; Johannessen and MacLennan, 2007; Shipman, 2004).

Each of the variables explored in this study are listed below and are described later in this section.

- Bluff height
- Surface geology
- Toe geology
- Fetch
- Shore orientation
- Shoretype
- Beach substrate
- Tidal Range
- Latitude
- Permeable/Impermeable
- Percent shore down-drift
- Vertical land movement

Some site-specific contributors to bluff recession rates were not integrated into this analysis due to the unique nature of each bluff site. Other elements were not included due to data limitations. For example, groundwater and the elevations of the beach waterward of the bluff are both relevant to bluff recession, however there is huge variability in groundwater and there is no reliable data source at the Sound-wide scale to reference either of these parameters. Additional data could later be added to these data as new regional datasets are developed in coming years.

Bluff recession generally occurs episodically in the Puget Sound region in what is commonly referred to as a “change event”. These change events typically occur on the order of once every 15–25 years. Therefore, bluff recession measurements must span at least 20 years to encompass at least one change event, to accurately reflect long-term bluff retreat rates (Keuler, 1988; Shipman et al., 2010). The dataset includes 185 long-term bluff recession rates from throughout the region that were measured across many years; ranging from 23 to 101 years. Figure 2, found in the Map Figures folio, displays all measurement locations. Recession rates were measured using two different approaches: historical air photo analysis in GIS and field-based measurements. Recession rates are reported as negative numbers, and represent annualized averages of multiple measurements (reported as FT/YR). Recession rates, measurement locations, measurement methods, and all supporting data are included in the attribute table of the project geodatabase and a large table in Appendix A.

Recession rates measured using historical aerial photography in GIS were compiled from several CGS studies in which the measurement methods were consistently applied (detailed methods described in *Aerial Photo Measurement Methods* below; (Coastal Geologic Services, 2015, 2013; Coastal Geologic Services and Northwest Straits Foundation, 2017; Keuler, 1988).

Field-based measurements were made by revisiting US Coast and Geodetic Survey (currently named the National Geodetic Survey, NGS) monuments in which the proximity to the bluff (crest or toe) was measured historically, and repeating the measurements (Figures 3 and 4). This field-based approach was first used by Ralph Keuler in his thesis research (Keuler, 1979) and then later when working for the USGS (Keuler, 1988). Table 1 and Figure 3 display the number and locations of existing and new bluff recession measurements and the methods employed. Not all of the original measurements were included in the final dataset that was subject to statistical analysis.

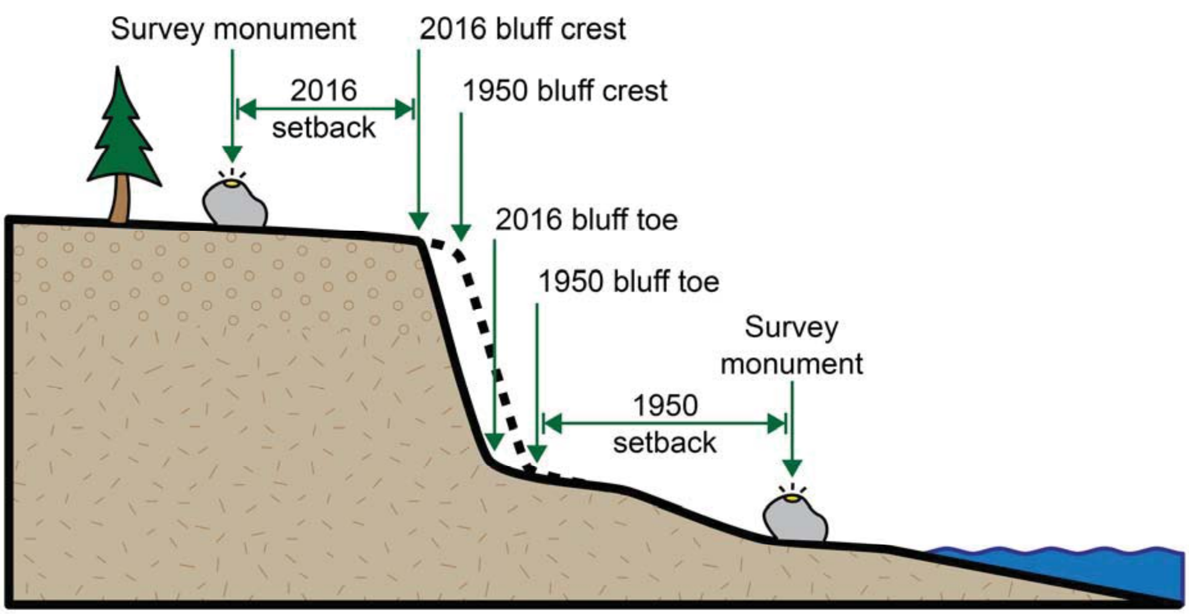

Figure 4. Bluff profile depicting bluff features and survey monuments used to measure long-term bluff recession.

Table 1. Number of bluff recession rate measurements associated with the different measurement methods.

Measurement Source and Method	Bluff Recession Rate Sties	Method Type
CGS, DSAS	106	Remote/Digital
Keuler, NGS	25	Field
CGS, NGS	54	Field

New measurement locations were carefully selected to augment the dataset to attain a more spatially-balanced representation across the region and categorical variables. Categorical variables include geomorphic shoretypes, geology bins, and shore orientation (described further in *Supporting Data Development*). A general stratification approach was applied to select bluffs to assure that the bluff characteristics explored in the analysis had adequate statistical power to detect a relationship between potential erosion drivers and rates of bluff erosion. The goal of the stratification process was to attain approximately 7–10 bluffs recession measurements for each of the major categorical variables (where possible), including—fetch (wave exposure categorized and continuous), bluff geology (toe and surface), and shore orientation—and adequate spatial distribution across the sub-basins that comprise the Puget Sound region.

In total, 106 bluff recession measurements were made using aerial photo methods and 79 bluff recession measurements were made using the field-based method, described further below.

Bluff recession measurement sites were not selected completely at random. Instead, various datasets were referenced as part of the site selection process. The stratification and measurement methods applied likely contributed some bias in the data collection, which is addressed in the discussion of results later in this report. The most limiting data source guiding the site selection process was bluff stratigraphy data, which was required to identify bluff toe geology and whether or not the bluff consisted of permeable overlying impermeable geologic units.

The availability of higher-quality historical air photos (e.g., those featuring fine-focused images, a lack of shading of bluff features, and an absence of additional (potential) sources of interference) also influenced site selection. Potential sources of interference were identified and intentionally avoided during the site selection process including: nearshore structures that could focus or attenuate wave energy such as a breakwater, jetty, or adjacent shore armor that was constructed low on the beach, bedrock promontories, or large deep-seated landslide complexes. The goal of the study was to measure bluff recession rates that would be representative of conditions across the region, rather than capture anomalous conditions. Although large complex landslides were commonly avoided, there were still several smaller landslides that were included in a limited number of bluff measurements.

Aerial Photo Measurement

Bluff recession rates were compiled into a database from a number of previous CGS studies in which the measurement methods were consistently applied using a similar stratification approach. The existing bluff recession database was augmented with new measurements, for a total of 106 digitally-measured bluff recession locations.

Historical vertical aerial photos were compiled and georeferenced for each of the sampled areas. Georeferencing error was kept to a minimum (less than 5 foot (FT) root mean square error (RMSE)), and control points were placed around the bluff to assure local accuracy. Some of the bluffs identified for analysis did not have adequate aerial photography coverage, meaning that there were not adequate control points for accurate georeferencing, or the bluff was shaded to the degree that features could not be interpreted with adequate certainty for this analysis. These bluffs were replaced with another site that met the stratification criteria.

Bluff recession measurements referenced the bluff crest most frequently, accounting for 59% of the measurement locations. In some cases when using historical air photos, the bluff crest shaded due to vegetation, and the bluff toe was selected (39%) as the preferred shoreline proxy. The shoreline proxy used to measure the recession rate was noted in the attribute table as well as the year that feature represented.

The bluff feature (either toe or crest) that could be delineated from the historical imagery with the greatest certainty was selected for analysis in ESRI ArcGIS. The selected proxy was then digitized along the same 500–1000-FT reach of continuous shore (average reach length 934 FT) from both the current and historical imagery at 1:500 to 1:800 scale. Breaks in the line were drawn in areas where the shore was too heavily forested to discern the location of the bluff crest. If conditions such as bluff height, geology, or shore orientation changed substantially along a segment of bluff, then the digitized line was truncated so as to keep each bluff recession measurement representative of a consistent combination of bluff characteristics.

Different historical aerial photos were used for different areas, based on availability and the ability to clearly view the selected proxy with a high level of confidence. Older aerial photos were typically 1:10,000–1:12,000 scale and mostly ranged between the years 1957 and 1969. Some sites were measured using 1976–1977 vertical aerial photos at 1:6,000 scale. Current feature locations were digitized from the most recent high resolution orthorectified imagery (generally within the last 10 years) or from a LIDAR Digital Elevation Model (DEM). Many sites used a combination of both. Recent LIDAR data were only used for bluff crest measurements as the toe of the bluff can be smoothed in the process of processing LIDAR data, resulting in an unnecessary additional source of error.

Digitizing bluff crests from LIDAR was guided by draping a partially transparent orthorectified photo over a hillshade created from the LIDAR DEM. In addition, a slope change raster was created from the DEM to support the identification of the location at which the greatest changes in relief occurred along the bluff (i.e., the crest, Figure 5).

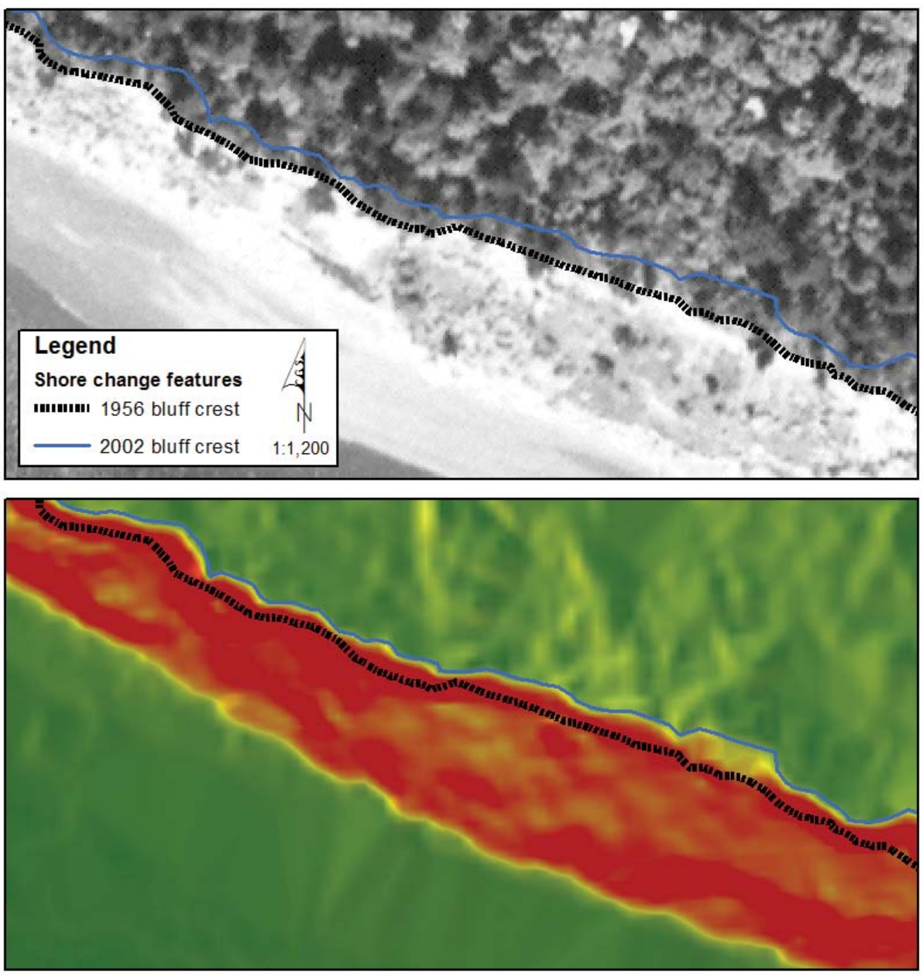

Figure 5. Bluff crest digitizing example from a 1956 historical vertical image (top) and a 2002 LIDAR slope change imagery of a bluff on southwest Camano Island. The distance between the two bluff crest lines represents the measured bluff crest recession across the period of analysis.

Feature digitizing was completed by the same staff member to the greatest extent possible to assure consistency in feature interpretation, and to preclude unnecessary bias associated with multiple analysts. All feature digitizing was QA/QC'd (quality assurance/quality control) by senior coastal geologist Jim Johannessen or senior coastal geomorphologist Andrea MacLennan to improve consistency in feature interpretation. After quality assurance revisions were applied, the data were ready for digital analyses.

The Digital Shoreline Analysis System (DSAS) is a software application that was developed by the Environmental Systems Research Institute (ESRI) and the United States Geological Survey (USGS). DSAS computes rate-of-change statistics for a time series of shoreline vector data. DSAS automates the shore change process, allowing for greater efficiency, and reduces the opportunity for error. Prior to running the tool, baselines were created from which transects would be drawn perpendicular to the shoreline. Baselines were created by exporting sample shoreform reaches of the WDNR ShoreZone shoreline (WDNR 2001) and buffering those reaches landward of the feature digitizing. Transects were spaced at 20-meter (65 FT) intervals across the sampled bluffs (Figure 6). DSAS then calculated the distance between each shoreline feature and calculated an end point rate (EPR), which equates to the measured distance between the two features (current and historical) divided by the number of years between those features (e.g. 1957 and 2009, 52 years). EPR measurements were then analyzed within each individual bluff together with supporting data.

Figure 6. Example digitized bluff toe and 20 meter/65 FT transect spacing.

A secondary QA/QC review of all bluff recession measurements was performed to identify outliers and other potential erroneous data points. The data points that were greater than 2.5 standard deviations from the mean were attributed to measurement error or poor image quality and eliminated from the analysis.

Field-Based Measurement

Direct field-based bluff recession measurements were conducted by repeating historical measurements between the bluff and monuments installed by the US Coast and Geodetic Survey (USCGS) in coastal areas. This method was originally used and described by Ralph Keuler while working on his thesis research at Western Washington University (Keuler, 1979) and later for the USGS in the Port Townsend 1:100,000 scale quadrangle (Keuler, 1988). Site selection was limited to locations in which there was a historical monument with additional detailed notes and historical measurements to the bluff crest or toe that could be repeated to obtain a long-term recession rate (Figures 7 and 8).

Figure 7. Repeated measurement from toe of bluff to NGS monument.

Figure 8. Examples of USCGS monuments, which were often set in concrete or large, typically stationary boulders.

The historical measurements are stored in the survey monument records which are maintained by the National Oceanographic and Atmospheric Administration (NOAA) and by the Washington State Bureau of Maps and Surveys. Field-based measurements included detailed descriptions of reference points and monument locations, which made repeating measurements straightforward, with little opportunity for measurement error. Field-based measurements were not used in Clallam and San Juan Counties as other researchers have already compiled high-resolution, long-term bluff recession measurements from that portion of the region (Coastal Geologic Services, 2013; Kaminsky et al., 2014; Parks et al., 2013).

Monuments and reference marks were typically located on the beach or bluff toe, and sometimes landward of the bluff crest. The proximity to the bluff toe or crest was recorded by the original surveyors at the time of installation and occasionally when revisited from individual monuments or markers (Figure 4). In some cases, the mapped monuments were no longer in place due to erosion or other land use changes. In addition to detailed historical measurements to a repeatable shoreline proxy, a stable monument installation was required, such as on a very large boulder on the beach that was found in upright position, or on upland monuments away from erosion or mass wasting processes. Monuments that appeared to have shifted over time were not used. Approximately 20% of the sites visited did not result in a bluff recession measurement due to degraded, moved, or lost monuments.

In some cases, multiple historical measurements were available, both temporally as well as spatially. In the case of multiple measurements over time, the oldest and also apparently most accurate measurement was used when calculating the overall erosion rate. For example, a measurement of "about 50 yards from the bluff toe" was considered of poor quality, while "32.5 feet from the bank" was considered of higher quality. Where multiple spatial measurements were made (e.g., from the main monument and a reference mark), the average rate across the individual measurements was reported.

Supporting Data Development

Several datasets were referenced and some developed to inform and explore the relative influence of various bluff characteristics (variables) to bluff recession rates. The source of each supporting dataset is described further below. All supporting data is included in the attribute table of the bluff recession database, regardless of whether or not the analysis results showed that variable to be of influence to bluff recession.

Bluff Height

The bluff height field was populated by identifying the maximum height of the bluff at the crest using LIDAR data (Figure 9).

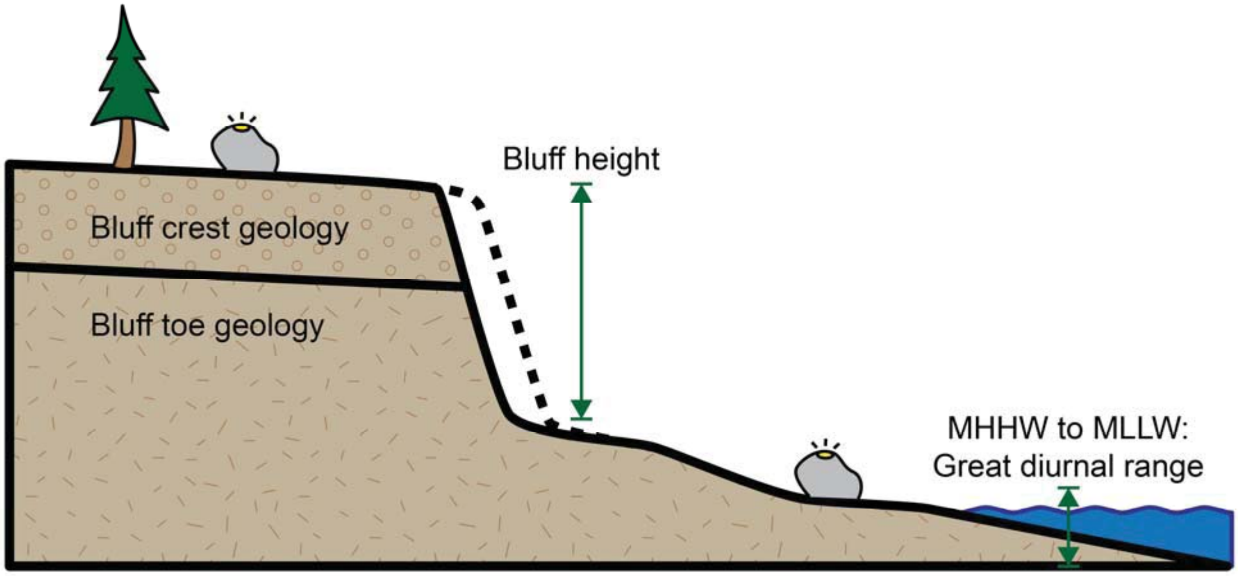

Figure 9. Bluff profile depicting bluff characteristics (variables) explored in relation to long-term bluff recession.

Surface Geology

The surface geology attributed to the bluff recession measurement was the mapped geology unit at the crest of the bluff (Figures 9 and 10). The preferred data source was the highest resolution surface geology mapping available, which in most cases was the Washington Division of Geology and Earth Resources (WDGER) 1:24,000, 7.5-minute quadrangle surface geology mapping. Where 1:24,000 scale mapping was unavailable, WDGER 1:100,000 surface geology mapping was referenced.

The geology units were categorized into four bins based on their similarity in sediment composition, consolidation, and general resistance to erosion. The units that were assigned to the different bins are displayed in Table 2.

In many cases, the surface geology unit only represents the overlying units of a given bluff's stratigraphy, and one or more underlying units are found lower on the bluff. Figure 10 provides an example of how the surface geology data was referenced for each bluff measurement location.

Table 2. Geologic units assigned to different bins for analysis. These bins were used for both bluff toe and surface geologies. Geologic unit abbreviations are found in Appendix B.

Bin	Description	Abbreviated Surface Geology Units
1	Till, cemented conglomerates, Kitsap Fm	Qt, Qvt, Qvt1, Br, Qgt, Qgt(u), Oem(q)
2	PreFraser sediments, Olympia beds, older fine grained deposits	Qns, Qco, Qpog, Qps, Qpg, Qpoc, Qpof, Qpfn, :Qvlc, Qs, Qo, Qgpc
3	Glaciomarine drift, Whidbey Fm	Qve, Qe, Qvrmd, Qvrms, Qvrmo, Qvmre, Qdm e, Qgdm ed, Qgics e, Qgom e, Qgme ec,
4	Advanced and recessional outwash, unconsolidated deposit, Mass Wasting deposits	Qva, Qve, Qga, Qga v, Qvr, Qd, Qls, Qgap, Qgas, Qga, Qguc, Qd, Qgof, Qa,

Toe Geology

Toe geology data were compiled from various data sources including field observations, field photos, geology profile data from WDGR 1:24,000 surface geology maps, and Washington Coastal Zone Atlas or USGS stratigraphy sections (Figure 10). Similar to surface geology, toe geology was categorized using the same bins shown in Table 2. A map of stratigraphy locations is found in Appendix C. A geodatabase of the stratigraphy sites with associated data has been compiled as part of the ancillary project deliverables.

Fetch

Fetch is the overwater distance over which wind-generated waves develop. New fetch measurements were applied for use in this analysis and a parallel mapping project for the Estuary and Salmon Restoration Program (ESRP). The new fetch data improve upon past fetch measurements reported in the WDNR ShoreZone database (WDNR, 2001). The new fetch data are sourced from a raster that was developed using the USGS Waves Toolbox, following the Shore Protection Manual (SPM) method of creating an averaged, effective fetch measurement (USGS, Upper Midwest Environmental Sciences Center, 2012). This checks fetch for each raster cell (here, 100 FT squares), for each possible wind direction (here, every 2 degrees). For each of those possibilities, fetch was averaged at 3-degree intervals over a 24-degree swath. For example, when evaluating a cell for effective fetch from the north (0°), fetch from 348°, 351°, 354°, 357°, 0°, 3°, 6°, 9°, and 12° were averaged. Figure 11 compares the previous and newly updated fetch measurement methods.

Fetch measurements for each site were linked from the center point to the underlying raster cell. Figure 12 displays the bluff recession measurement sites with the updated fetch raster shown on the waterward shore.

Shore Orientation

The orientation of the measurement location was assigned as northern or southern exposure. If the shore was oriented directly east or west, then the orientation that had the greatest fetch (either north or south) was assigned. For example, the shore in Figure 11 would be categorized as oriented to the south. Because both the prevailing and predominant winds come from the south, it has been hypothesized that bluffs exposed to the south generally incur more erosion during change events than those exposed to the north or other aspects (Downing, 1983).

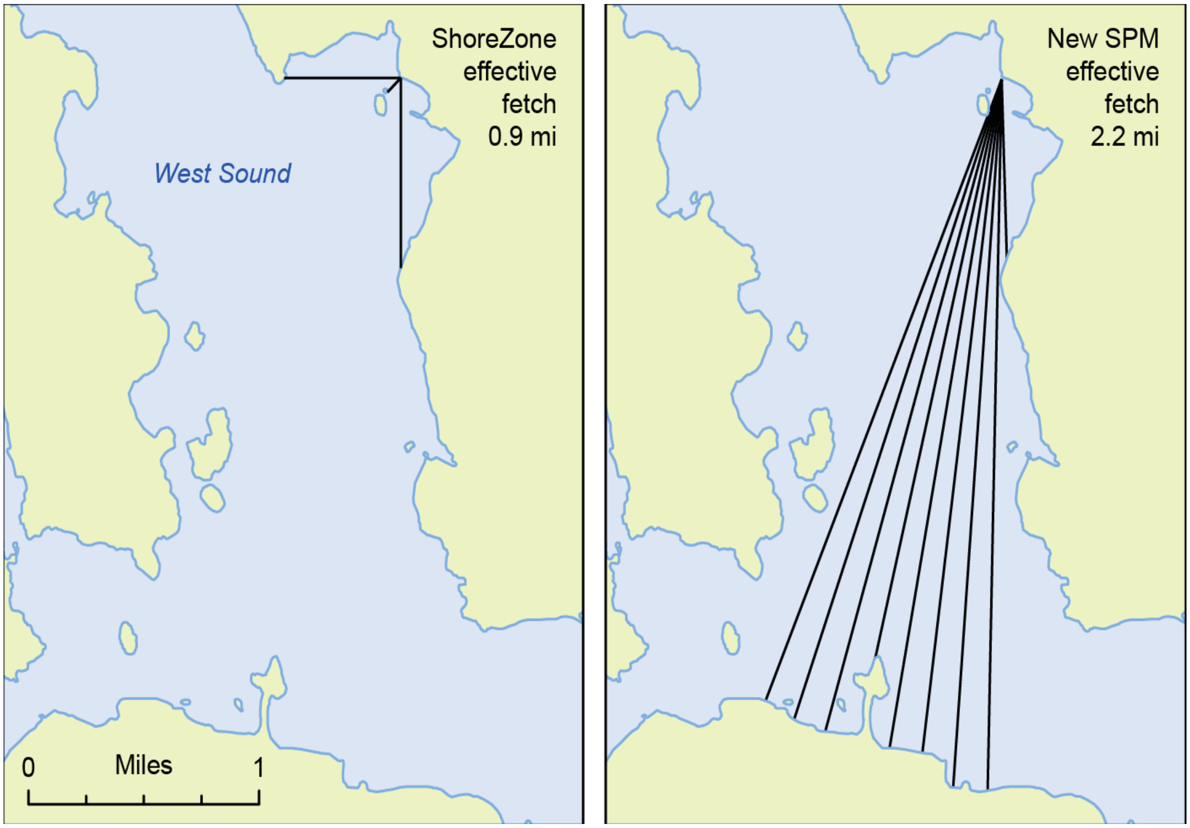

Figure 11. Contrasting fetch measurement methods from ShoreZone (WDNR 2001) and new SPM fetch measurements.

Shoretype

The shoretype of the measurement location was sourced from the *Puget Sound Feeder Bluff Mapping* geodatabase (MacLennan et al. 2013). Shoretype definitions are found in Table 3 and representative shoretypes shown in Figure 13. None of the bluff measurement locations were located behind armored shores. Figure 12 displays the shoretype for each bluff recession measurement site.

Table 3. Shoretype descriptions from *Puget Sound Feeder Bluff Mapping*

Shoretype	Description
Feeder bluff exceptional	Coastal bluff with active erosion and/or mass wasting which periodically supplies substantial volumes of sediment to the nearshore in greater quantities with a shorter recurrence interval than feeder bluffs. The bluff face typically has little to no vegetation with active landslides and toe erosion, and may include colluvium and toppled large woody debris.
Feeder bluff	Coastal bluff with active erosion and/or mass wasting which periodically supplies moderate volumes of sediment to the nearshore with a longer recurrence interval than feeder bluff exceptional segments. The bluff face typically has vegetation indicative of disturbance with evidence of landslides and toe erosion.
Transport zone	A bluff or bank which supplies minimal but not appreciable sediment input to the nearshore from erosion/mass wasting, and does not have an accretion shoreform present. Littoral sediment is typically transported alongshore. The bluff face typically has considerable coniferous vegetation with few signs of disturbance from landslide activity or is of very low relief such that sediment input is very limited.
Pocket beach	A beach that is contained between two headlands that essentially functions as a closed system in terms of littoral sediment transport.

a) Feeder bluff exceptional — Double Bluff, Island County

b) Feeder bluff — Anderson Island, Pierce County

c) Transport zone — Guemes Island, Skagit County

d) Pocket beach, San Juan County

Figure 13. Different bluff shoretypes used to categorize bluff locations in this study (MacLennan et al., 2013).

Substrate

Substrate data were integrated from the cross-shore descriptive data from the ShoreZone Inventory (WDNR 2001). These data were included experimentally, as it was not known how comprehensive the data were and if they would be effective in this analysis. Unfortunately, these data were not as useful in this application; substrate was noted at inconsistent elevations across the different locations, therefore it was not appropriate to compare the data across different bluff measurement locations.

Tidal Range

Great diurnal tidal range was estimated using the NOAA VDatum software by first calculating the latitude and longitude for each measurement location and referencing that location in VDatum, which then reports the elevation of Mean Higher High Water and Mean Lower Low Water. The difference between the two values was the reported maximum tidal range for the site (Figure 9). It has been documented in other coastal environments that erosion rates are higher in areas with narrower tidal range (Rosen, 1977). A map showing the distribution of tidal range within the Puget Sound region is shown in Figure 14.

Permeable over Impermeable

The permeable over impermeable geology data were categorical data meant to differentiate between bluffs with stratigraphy comprised of a mix of permeable geologic units over impermeable units from bluffs with more homogeneous or similar strata. Shipman (2004) describes the influence of stratigraphy on the bluff profile and hydrologic characteristics that influence mass wasting mechanisms. For example, many high bluffs around the Puget Sound region have a visible mid-slope bench that marks the contact between permeable advance outwash deposits and underlying impermeable lakebed clays. Saturation along this contact often contributes to upslope failures leading to more complex bluff profiles, containing both steep and gradual segments. In contrast, bluffs with more homogenous stratigraphy typically have simpler erosion and mass wasting process that result in a more uniform bluff slope at the angle of repose (Shipman, 2004).

The data referenced to populate this field largely included stratigraphy data that were previously compiled for the bluff toe geology attribute, but also included field observations, and some professional judgement calls from senior geologist Jim Johannessen, who had on-the-ground knowledge from several sites measured during site visits. There were insufficient data available to populate this field for a considerable number of sites.

Percent Down-Drift

CGS recently completed linear referencing for all Puget Sound region net shore-drift cells. The linear referencing data were used to identify the distance that each measurement site was located down-drift from the drift cell origin, relative to the overall length of the drift cell. It has been hypothesized over the years that erosion rates are typically higher near the drift cell origin (Jacobsen and Schwartz, 1981). These data were developed to help explore this question.

Vertical Land Movement

Vertical land movement (VLM) data were derived from a preliminary assessment of vertical land movement to support sea level rise planning for the Washington Coastal Resilience Project (in prep.). VLM was used as a proxy for relative sea level change rates, which assumes that each of the sites in Puget Sound is subject to identical absolute sea level change rates.

VLM values were derived for that project from four different data sources:

1) Point estimates derived from continuous GPS (cGPS) stations. The rates from 5 different cGPS datasets were averaged.
2) Repeated first- and second-order leveling surveys of National Geodetic Survey monuments with assessment and corrections applied where necessary (Burgette et al., 2009).
3) VLM estimates from tide gauge sites that were the average of multiple estimates derived from both "single-differencing" tied to cGPS and, in some cases double-differencing (see (Santamaria-Gomez et al., 2013) tied to satellite altimetry.
4) A tectonic deformation model with 1/10th degree resolution

A nearest neighbor interpolation was used to assign VLM to each bluff recession measurement location.

Statistical Methods

The statistical methods employed in this study were intended to identify the variables that contribute to long-term bluff recession rates, and then develop a model that effectively represents those relationships. Ordinary Least Squares (OLS) regressions were used to understand the relationship between the various bluff characteristics and the long-term recession rates. The final model would both maximize variance explained (r^2), and, more importantly, reduce the average residual error with which predictions about bluff recession could potentially be made (the Mean Residual Error).

The bivariate relationship between each variable and the long-term bluff recession rate, reported as the End Point Rate (EPR), was investigated for each site. This provided greater understanding of the baseline relationships in terms of direction, magnitude, and variance explained of the long-term recession rates. Next, all variables were combined into a multiple OLS regression model. An iterative process was used to determine which variables to include within the preferred model. Non-statistically significant variables ($p>0.05$) that also had the lowest standardized slope coefficient with respect to the long-term erosion rate (commonly referred to as the "beta" weight) were removed from the list of variables to potentially include in the preferred model. Each of the variables that were removed were then added back into the model one at a time and re-tested for statistical significance to assure that they were not excluded erroneously.

Results

The project was initiated by compiling many bluff recession rates from previous studies and subjecting those data to preliminary statistical analyses. The objective of the preliminary analysis was to determine if there were enough individual bluff measurement sites for each of the different variables to assure the analysis had adequate statistical power and to understand initial relationships between variables and long-term bluff recession rates. Initial results guided the subsequent data collection effort and data refinement such as developing new fetch data, finding a different data source for tidal range (initially the WDNR ShoreZone, later switched to NOAA/VDatum), and identifying new bluff recession measurement locations.

Recession rates were measured from a total of 185 shore segments throughout the Puget Sound region (Figure 15, Appendix A). A handful of recession measurements were omitted from final analysis: one observation had a Feeder Bluff — Talus shoretype; two used the log line as a shoreline proxy; and three observations contained potentially erroneous measurements of the long-term recession[1]. The final analytical sample therefore contained 179 measurements.

Descriptive Results

Data analysis was initiated by evaluating the distribution and descriptive statistics of long-term bluff recession rates (EPR in FT/year), the categorical data, and each of the continuous variables used in the study (Table 4).

The average long-term recession rate was -0.29 FT/YR (all recession rates are negative numbers), with a standard deviation of 0.21 feet per year across all the bluffs sampled (Figure 15). The median bluff recession rate was -0.25 FT/YR and the mode was -0.14 FT/YR. Recession rates ranged from -0.03 to -1.12 FT/YR. The number of years used to calculate change ranged from 23-101 years. The average number of years that the measurements were based was 44.2 years, with a median of 49 years. The frequency distribution of the highest change rates can be observed in Figure 16. The spatial distribution shows more rapidly receding bluffs found in the Northwest Straits and more slowly eroding bluffs found in the sheltered, lower energy shores of southern Puget Sound (Figure 15).

Table 4. Descriptive statistics of study variables (continuous). EPR = End Point Rate (Bluff recession rate). Erosion is a negative value, therefore the lower the number the greater the rate of erosion.

	Descriptive Statistics of Study Variables (Continuous)				
Variable	Mean	Standard Deviation	Median	Minimum	Maximum
EPR (FT/YR)	-0.29	0.21	-0.25	0.03	-1.12
Fetch (MI)	10.02	12.30	6.43	0.49	61.32
Tidal Range (FT)	10.58	2.40	11.21	6.98	14.53
Bluff Height (FT)	89.45	77.37	70.00	10.0	360.00
Percent Down-drift	0.57	0.29	0.60	0.00	1.00
Vertical Land Movement (FT)	-0.0011	0.0047	-0.0030	-0.0099	0.0121

N=179 for all variables except Drift Cell Percent Down Drift (N=161). We report the standard deviation of EPR to three significant digits as this represents the unadjusted error in EPR before modeling this variation in the OLS regression models.

[1] We supported our hypothesis that these observations contained erroneous measures of the long-term erosion rate by initially including the observations within the multiple regression analysis. We found that each observation's residual was more than four standard deviations below the mean. In a normal distribution, we would only expect to observe a bluff with these characteristics less than 0.01% of the time, so we believe this is sufficient evidence for removal.

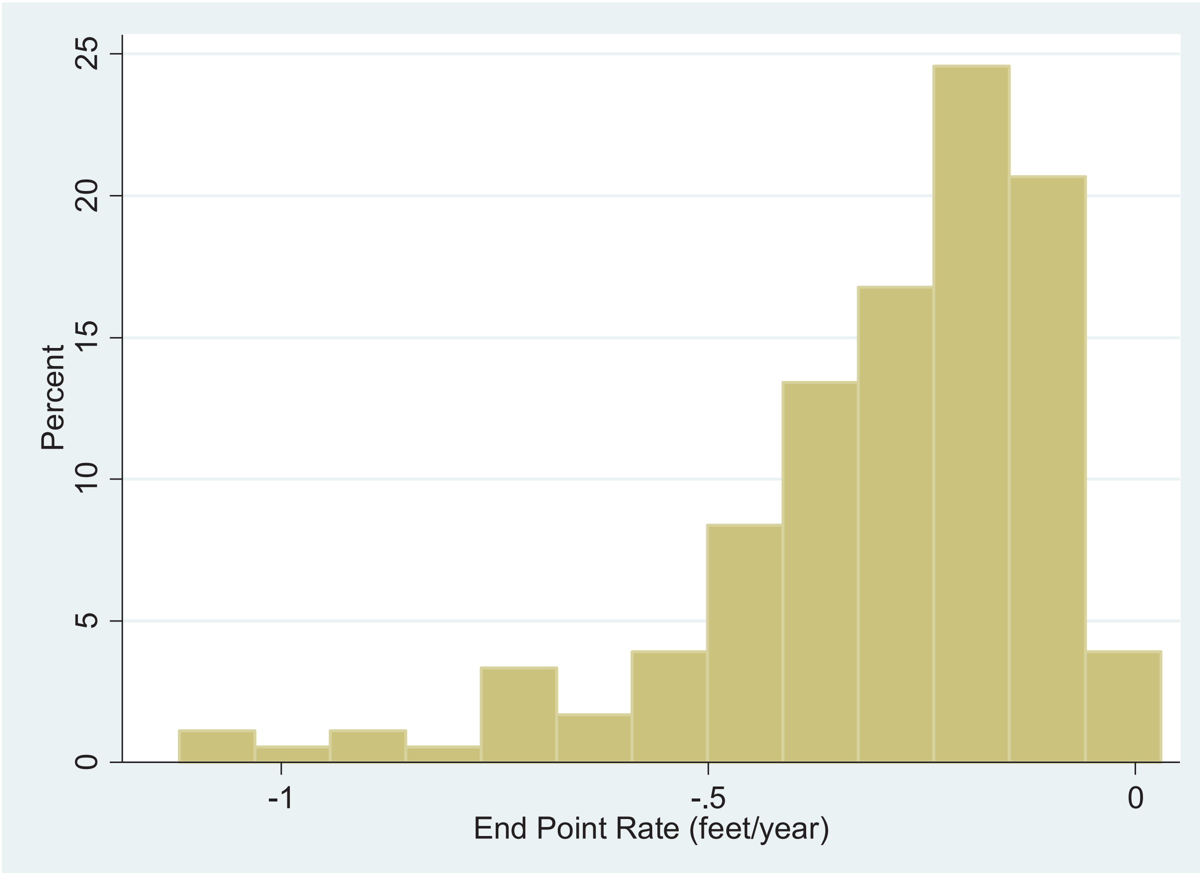

Figure 16. Frequency distribution of all long-term bluff recession rates, reported as End Point Rate (feet/year).

The mean fetch distance was 10 miles (Standard Deviation (SD) = 12.30), and ranged up to a maximum of 61 miles (Table 4). The variation in tidal range was relatively small (SD = 2.40 feet) with a mean of 10.58 feet. The average bluff measured 89.45 feet in height, ranging from 10 to 360 feet (SD = 77.39 feet). On average, recession rates were measured from bluffs that were located 57 percent of the drift cell length down drift from the cell origin (SD = 0.29). For the regression analyses, the fetch and bluff height data were transformed with a log transformation due to the skewness of the underlying distributions of these variables[2]. Based on the assumptions of the statistical analyses applied here, no other data needed transformations.

The categorical data are described in Table 5. For each of the categorical measurements, the variables were recorded as a series of indicator variables. Fifty-eight percent (58%) of the measurement sites were Feeder Bluffs, while 18 percent were Feeder Bluff Exceptional, 8 percent Pocket Beach, and 17 percent Transport Zone. Mean EPR across each of the shoretypes exhibited a statistically significant difference ($p \leq 0.05$), with the Feeder Bluff Exceptional shores exhibiting the greatest erosion rates.

[2] We ultimately decided to use the original, non-transformed measure of SPM fetch in our OLS regression analysis. We did not observe any greater degree of non-linearity, heteroskedasticity, or non-normality of the residuals when comparing the models using the two measures. In addition, the model using the original measure contains a higher r^2 and lower EPR mean residual error.

Table 5. Descriptive statistics of study variables (categorical).

Variable	Proportion	N	Group Mean EPR	Group EPR SD
Shoretype(*)				
Feeder Bluff Exceptional	0.18	32	-0.42	0.24
Feeder Bluff	0.58	103	-0.30	0.20
Transport Zone	0.17	30	-0.19	0.15
Pocket Beach	0.08	14	-0.19	0.07
Orientation				
South	0.66	118	-0.29	0.18
North	0.34	61	-0.30	0.25
Measurement feature(*)				
Bluff toe	0.50	89	-0.20	0.12
Bluff crest	0.36	65	-0.38	0.21
No data(k)	0.14	25	-0.40	0.28
Permeable/Impermeable				
Yes	0.18	32	-0.28	0.24
No	0.28	51	-0.30	0.17
No data	0.54	96	-0.29	0.21
Surface Geology (bins)				
Till	0.34	61	-0.29	0.19
Pre-Fraser units	0.11	20	-0.24	0.16
Glaciomarine drift	0.23	42	-0.34	0.25
Advance/recessional outwash	0.31	56	-0.28	0.19

N=179. Proportions of variables may not add to one due to rounding.
(*) Difference in EPR statistically significant between groups based on one-way ANOVA F-Test ($p \leq 0.05$).
(k) Indicates all missing observations from Keuler Field or Keuler Thesis observations.

About two-thirds of the measurements were from south-oriented bluffs. There was a minimal average EPR difference compared to north-oriented bluffs. Half of the bluff EPRs were measured from the bluff toe, with another 36 percent from the bluff crest. As noted in the footnote of Table 5, there is no information about the bluff feature from which the EPR was measured for 14 percent of bluffs. These measurements were conducted by Keuler from his USGS work (Keuler, 1988) or thesis research (Keuler 1979). Observations from the bluff toe had a lower mean EPR than measurements from the bluff crest or those that are missing.

Eighteen (18) percent of bluffs did not have permeable over impermeable bluff stratigraphy, while 28 percent of bluffs did have permeable over impermeable bluff stratigraphy. There were no data available for 54 percent of the bluffs sampled. Bluff surface geology consisted of 34 percent of bluffs with Till surface geology, 11 percent with Pre-Fraser units, 23 percent Glaciomarine units, and 31 percent comprised of Advance/Recessional or similarly less consolidated deposits. There were no statistically significant differences in EPR by surface geology.

Bivariate Results

The results of exploring the bivariate relationships between each variable and long-term bluff recession rates are shown in Tables 6 and 7. Of all the variables evaluated, measured fetch exhibited the strongest overall correlation with EPR (r=-0.43), which is overall negative and moderate in strength. Tidal range had a positive and weak-to-moderate correlation with EPR (r=0.29) while the natural log-transformed bluff height had a negative and weak correlation with EPR (r=-0.24). There was a negative and weak linear association between drift cell percent down drift and EPR. Vertical land movement had a very weak correlation with EPR (r=-0.09) and the slope with EPR was not statistically significant. For the continuous variables, only fetch (r^2=0.184) and tidal range (r^2=0.083) explained any meaningful variance in EPR.

Table 6. Analysis of individual continuous variables with EPR.

Variable	Regression Slope	Pairwise Correlation	r^2	EPR Mean Residual Error
Fetch (MI)	-0.01 *** (0.00)	-0.43	0.184	0.185
Tidal Range (FT)	0.02*** (0.01)	0.29	0.083	0.196
Log Bluff Height (FT)	-0.05*** (0.01)	-0.24	0.058	0.199
Percent Down-drift	-0.01* (0.01)	-0.16	0.026	0.202
Vertical Land Movement (IN/YR)	-0.33 (0.025)	-0.09	0.008	0.204

~p≤0.10, *p≤0.05, **p≤0.01. N=179. Heteroskedasticity-robust standard errors in parentheses. Slope estimates of rate of EPR listed for unit changes in parentheses of continuous variables. Correlation and model summary statistics also displayed.

For the categorical variables, only shoretype (r^2=0.133) and bluff feature (r^2=0.205) explain any meaningful variance in EPR (Table 7). Vertical land movement had a very weak correlation with EPR (-0.09) that was not statistically significant.

Table 7. Analysis of individual categorical variables with EPR.

Variable	r^2	EPR Mean Residual Error
Shoretype	0.133	0.192
Orientation	0.002	0.205
EPR Bluff Feature	0.205	0.183
Impermeable/permeable	0.002	0.206
Surface geology	0.018	0.204

N=179. Model summary statistics displayed for OLS regression models of each individual categorical predictor with EPR.

OLS Regression Results

After investigating each variable individually, the multiple regression model results were summarized (Table 8). The multiple OLS regression model is shown in the column labeled “initial model” in Table 8. An iterative process was used to determine which variables to include within the preferred model, which are shown in the column labeled such (Table 8). The OLS regression results were evaluated separately and are also shown one variable at a time in for individual continuous predictors in Table 6. Data plots from analysis are included in Appendix D.

Non-statistically significant variables (p>0.05) that also had the lowest standard slope coefficient (commonly referred to as the "beta" weight) were removed from the list of variables. The variables that were removed from the list of potential preferred variables include (in order of removal):

- Shore orientation
- Percent down-drift
- Bluff height
- Permeable/impermeable strata
- Vertical land movement

Each of the five excluded variables were added back into the model one at a time and re-tested for statistical significance to assure that they were not excluded erroneously and may include a potentially statistically significant variable along the way. However, as each of the five excluded variables remained not statistically significant (p>0.05), it was concluded that they should not be included in the final model.

Multicollinearity was observed between tidal range and both latitude (-0.88) and vertical land movement (-0.65). Tidal range explained more variability when compared with latitude and vertical land movement, and was therefore selected as the preferred variable for inclusion in the final model. However, as the relationship between tidal range and latitude is so strong, latitude could be used as an effective proxy for tidal range in the absence of tidal range data.

The final (preferred) model is written symbolically below:

$$
\begin{aligned}
EPR_i = \hat{\beta}_0 + \hat{\beta}_1 FBEShore_i + \hat{\beta}_2 PBShore_i + \hat{\beta}_3 TZShore_i + \hat{\beta}_4 PFSurfGeo_i + \hat{\beta}_5 GlaSurfGeo_i \\
+ \hat{\beta}_6 ARSurfGeo_i + \hat{\beta}_7 BluffCrest_i + \hat{\beta}_8 MissFeature_i + \hat{\beta}_9 FinFetch_i \\
+ \hat{\beta}_{10} TidalRange_i + \hat{\varepsilon}_i
\end{aligned}
$$

Here, the measured End-Point Rate (EPR, or the long-term erosion rate) for a bluff (*i*) is a linear prediction of the bluff's shoretype (Feeder Bluff Exceptional, Feeder Bluff, Transport Zone or Pocket Beach), category of surface geology (PreFraser, Glaciomarine, or Advance/Recessional versus Till), bluff feature from which the EPR measure was taken (bluff crest or missing[3] versus bluff toe), fetch, and tidal range. With this model, the slope for each of these characteristics ($\hat{\beta}_1$-$\hat{\beta}_{10}$) along with a random intercept term ($\hat{\beta}_0$) was estimated. Heteroskedasticity-consistent standard errors ($\hat{\varepsilon}_i$) were included for all OLS regression models. The inclusion of these robust standard errors results in larger slope estimate standard errors while mitigating the impact of a slight degree of underlying heteroskedasticity in the preferred model.

Feeder Bluff Exceptional shores had bluff recession rates of 0.10 feet/year faster than Feeder Bluffs (p=0.008), controlling for surface geology, bluff EPR feature, measured fetch, and tidal range. On the other hand, the recession rates of Pocket Beaches and Transport Zones was 0.16 FT/YR and 0.08 FT/YR slower than Feeder Bluffs, respectively (PB: p≤0.001; TZ: p=0.009). Bluffs with advance or recessional surface geology had an erosion rate of 0.10 feet/year less severe than bluffs with till surface geology, all

[3] We include an indicator in the OLS regression model for each of the 25 observations where the bluff features from which the EPR was taken is missing in the data. Each of these observations came from either Keuler field work or Keuler thesis observations. This enables us to retain these 25 observations within our analysis and to use bluff feature as a potential predictor to account for mean differences in EPR based on where the EPR measure was taken.

else equal (p=0.001). There was no statistically significant difference between bluffs with Pre-Fraser or glaciomarine surface geologies and those with till surface geology.

When the EPR was measured from the bluff crest, it was 0.12 FT/YR faster than when measured from the bluff toe, controlling for all other factors ($p \leq 0.001$). This was likely due to the added error associated with the bluff recession measurement methods, and is discussed further in the next section. After controlling for other factors, no significant difference was detected between the Keuler field or Keuler thesis bluff recession measurements (those missing the bluff feature from which the EPR was taken) and the bluff toe observations. This suggests that the Keuler measurements are no different than those taken from bluff toes and should remain in the analysis. Accounting for the other variables, for every two-mile increase in measured fetch, an associated 0.01 FT/YR increase in the erosion rate can be expected (p=0.001)[4]. Additionally, each 1 FT increase in tidal range is associated with a 0.02 FT/YR decrease in the recession rate, all else equal (p=0.002).

These five variables explain 41.5% of the overall variation in EPR. The combination of variables included in the preferred model reduces the mean residual error of EPR to 0.161 FT/YR. This represents a 21.4% improvement in estimation error when using these variables included in the preferred model to estimate bluff recession rates. No evidence of multicollinearity or non-normality of the residuals was found in the preferred model. Any slight degree of heteroskedasticity (primarily for those bluffs with the largest EPR) is accounted for in the robust standard errors.

[4] The actual slope estimate is -0.005 feet/year for every mile increase in fetch, which is a higher level of precision than displayed in Table 6. This interpretation more appropriately captures the relationship between fetch and EPR.

Table 8. Multiple regression analysis with EPR for all variables as included in the initial model and the preferred model, in which only the variables with the strongest relationship to EPR were included.

Variable		Initial Model	Preferred Model
Shoretype [Feeder Bluff]	Feeder Bluff Exceptional	-0.10* (0.04)	-0.10* (0.04)
	Pocket Beach	0.12 (0.08)	0.16*** (0.04)
	Transport Zone	0.09* (0.03)	0.08* (0.03)
Surface Geology [Till]	Pre-Fraser	0.03 (0.04)	0.05 (0.04)
	Glaciomarine	0.05 (0.03)	0.05 (0.03)
	Advance/Recessional	0.10*** (0.03)	0.10*** (0.03)
EPR Bluff Feature [Bluff Toe]	Bluff Crest	-0.14*** (0.03)	-0.13*** (0.03)
	Missing	-0.05 (0.05)	0.00 (0.04)
	Permeable/Impermeable Geology [No]	-004 (0.04)	
	Northern Orientation [South]	0.01 (0.03)	
	Measured Fetch	-0.01** (0.00)	-0.01*** (0.00)
	Tidal Range	0.02*** (0.01)	0.02** (0.01)
	Log Bluff Height	0.01 (0.02)	
	Drift Cell	(0.00) 0.00	
	Vertical Land Movement	-4.57 (3.36)	
	Intercept	-0.36	-0.45
	N	179	179
	r^2	0.431	0.415
	EPR Mean Residual Error	0.162	0.161

~p≤0.10, *p≤0.05, **p≤0.01. Heteroskedasticity-robust standard errors in parentheses. Slope estimates of rate of EPR listed for continuous variables. Difference-in-means of rate of EPR listed for categorical variables from reference group in brackets. Indicator for missing values of feature, slide plane risk, and drift cell included to maintain all observations and suggest missing observations are not statistically different from observed.

Discussion

The objective of this study was to better understand the range of long-term bluff recession rates in the Puget Sound region and the relative strength of the variables controlling that recession. Results identified several dominant variables that influence bluff recession that can be used to inform future planning, from restoration and regulations to future bluff studies. Each of the variables that affected bluff recession in a statistically significant way is discussed further below. Future users of these data should be informed of the full context of the data values, limitations (such as error and bias), and ways in which the data could be expanded upon in the future. Several opportunities exist to build on this foundation of data; these are described further below.

Fetch

Previous research has documented that one of the dominant drivers of coastal bluff recession is wave energy (Bray and Hooke, 1997; Emery and Kuhn, 1982; Shipman, 2004), for which fetch is a proxy. This study documents that fetch has the strongest relationship with long-term bluff recession rates in the Puget Sound region, when compared to the other variables explored. The Puget Sound region is often described as a fetch-limited environment (Finlayson, 2006; Johannessen and MacLennan, 2007); and the bluffs with low fetch are less subject to this force of change. This lack of wave-induced erosion on low-fetch bluffs may help to negate the perceived need for erosion control where it may not be necessary. These data may help nearshore managers to better understand where bluff recession rates may be slower than perceived and where structures should possibly be further set back from the bluff crest. As reported above, every 2-mile increase in measured fetch is associated with a direct 0.01 FT/YR increase in the recession rate. Pairing these results with wave modeling data (currently in preparation by USGS) could further document this relationship and the effectiveness of fetch as an analogue for wave energy.

Shoretype

Recent geomorphic shoretype mapping was completed in the Puget Sound region in 2013 by CGS (MacLennan et al., 2013). The shoretype mapping was largely qualitative, relying on mapping rules using beach and bluff features that indicated the degree of erosion, mass wasting, and deposition. Shoretypes were not previously linked with measured recession rates, although there was somewhat of a gradient of indicators that corresponded with the magnitude of recession. The results of this analysis provide a quantitative linkage between long-term bluff recession rates and geomorphic shoretypes within the Puget Sound region, which can be used to better understand the range of recession rates that occur along the bluffs that comprise the regions' shores.

This geomorphic shoretype mapping was recently refined and re-released and packaged with other nearshore data (including the fetch raster used to calculate fetch in this study) into a nearshore geodatabase for the *Beach Strategies* project (Coastal Geologic Services, 2017). These data are publicly available and enable users to pair shoretype and fetch data to improve planning and understanding of coastal bluff processes in the Puget Sound region. In some local jurisdictions, setback distance regulations are increasingly being applied by shoretype. These data further support this type of approach and provide additional data to inform the proposed setback distances.

Tidal Range

Another variable of influence to long-term bluff recession rates in this study was tidal range. Results of this analysis showed that for each 1 FT increase in tidal range (in this case, great diurnal tidal range), there is a 0.02 FT/YR decrease in the recession rate. Tidal range exhibited multicollinearity with latitude; therefore the latter was removed from the assessment. The (inverse) relationship between tidal range and latitude is most clearly observed by the maximum tidal ranges occurring in the southernmost reaches of the Puget Sound region (Figure 14). Tidal range gradually decreases moving north; however this pattern is complicated as tidal range increases again moving further north up the Strait of Georgia. The full extent of this pattern is not represented in the data as it is truncated by the Canadian border (Figure 14).

Tidal range was positively associated with bluff recession rate (a negative number), meaning that bluffs recede more rapidly in areas with a smaller tidal range. Smaller tidal ranges focus wave energy on a narrower portion of the beach profile as compared to larger tidal ranges (Rosen, 1977). Therefore, a smaller section of the beach or bluff toe is subject to wave action for a longer duration of the tidal cycle, resulting in greater change as compared to sites with larger tidal ranges. This process is compounded by the mixed semi-diurnal pattern of tides in the Puget Sound region which results in water levels being skewed toward the upward end of the tidal range (Finlayson, 2006).

Finlayson hypothesized that the upward skew in the semi-diurnal tidal curve for the Puget Sound region controls the zone of sediment transport on the beach (2006). Similarly, sediment transport occurring within a more focused band on the upper beach may influence the cycle of marine-induced bluff erosion. Rosen also documented that the supratidal elevations are higher in areas with larger tidal ranges, and lower in areas with smaller tidal ranges (Rosen 1977), resulting in more frequent inundation of the supratidal. The cycle of marine-induced bluff erosion is where sediment eroded from the base of the bluff (colluvium) protects the toe of the bluff from further wave attack while it is slowly removed by wave action. Once waves have eroded the colluvium, they attack the base of the bluff, causing bluff undercutting and erosion, and then the cycle repeats (Emery and Kuhn 1982). Therefore, bluffs with a narrower tidal range may possibly maintain wave-buffering colluvium for a shorter period of time, due to the likely greater sediment transport occurring on these beaches, resulting in shorter cycle of wave-induced erosion and slightly increased rates of long-term bluff recession at these narrow tidal range bluffs.

Bluff Geology

Three different parameters associated with bluff geology were analyzed in association with bluff recession: bluff crest geology, bluff toe geology, and whether or not the stratigraphy of the bluff consisted of permeable overlying impermeable strata. The only variable in which a significant relationship with bluff recession was documented was bluff crest geology. Surface geology is the most widely available geology data (WDGER). All bluff recession measurements had a reported bluff crest geology unit (or bin), which was not the case for the other geology variables. The widespread availability of these data increases their utility in the preferred model, as they are more practical than the other geologic data, which are not publicly available.

Bluff toe geology and permeable overlying impermeable stratigraphy were not available for all recession rate sites, resulting in a much smaller sample size. There is a possibility that sample size could have affected the statistical power of these results. Shipman, citing Gerald Thorsen's observations, concluded that bluff toe geology (the exposed strata at the toe of the bluff) was a controlling factor over bluff toe erosion. The mapping methods for bluff toe geology and permeable overlying impermeable strata varied considerably and could have affected the results. Because there is no single uniform database for bluff stratigraphy throughout the Salish Sea region, this will continue to be an issue when exploring stratigraphy data unless new field mapping can be conducted throughout, which was not possible in this study due to funding limitations.

It is also possible that the somewhat complex relationship between bluff geology and bluff recession is difficult to measure at a regional scale. Similar analyses have been conducted on long-term bluff recession rates and bluff geology in the Great Lakes region, in which considerable variability in bluff recession rates were explained by geology. However, those studies were conducted across a more limited spatial extent (Amin and Davidson-Arnott, 1997). Therefore it is recommended that these relationships be further explored in a higher resolution assessment of bluff recession. In addition, surface geology mapping rarely accurately captures the full geology of the bluff. In many areas, Vashon till, which was the major “capstone” geologic unit, often overlies less consolidated bluff geology (such as outwash sands).

Bluff recession rate had a weak (negative) correlation with bluff height (-0.24), indicating that greater erosion rates tend to occur on higher elevation bluffs. This relationship was not strong enough and did not explain any additional variability in recession rates, and therefore was not integrated into the final predictive model.

Bluff recession rates were affected by whether or not the rate was measured from the crest or toe (referred to as the measurement feature). After this result was identified, the data were explored more closely to better understand if this was an error or could be attributed to an artifact of the measurement methods. After review, it appeared that this result was likely a product of the bias and error margins associated with the bluff recession measurement methods and how they were applied. Cumulatively the error and bias resulted in much higher bluff recession measurements from bluff crests measured using air photos (DSAS method). Field-based bluff crest measurements were considerably lower than those measured using DSAS. Bluff toe recession was also more rapid than bluff crest recession measurements using historical air photos (Figure 17). The need to include the measurement feature as a variable in the preferred model reflects these relationships and emphasizes the need for further investigation into these relationships as a follow-up to this work.

Bluff recession measurements that were made from air photos tended to be applied to sites that were largely denuded of vegetation, thereby resulting in a clearly discernable bluff crest. Bluff crest was the more prevalently digitized shoreline proxy for air photo work, as scientific literature states that there is greater accuracy in using a more landward shoreline proxy, where possible. In contrast, field-based bluff recession measurements from NGS monuments were typically from more sheltered coastal environments that were typically heavily vegetated, precluding air photo analysis, and often referenced monuments on the beach or relative to the toe of the bluff. Another factor that likely contributed to bias was that old monuments were more likely to last a long time on the beach in areas with lower recession rates, as opposed to higher wave energy and higher bluff recession areas. In addition, several NGS monuments were not found and may have been lost due to coastal erosion, which could represent an additional source of bias. The significant difference in recession rates documented between these methods reduces the error in the predictive model. Although the results are not informative to the drivers of bluff recession, it reduces noise and enables a more accurate understanding of bluff recession rates in the Puget Sound region.

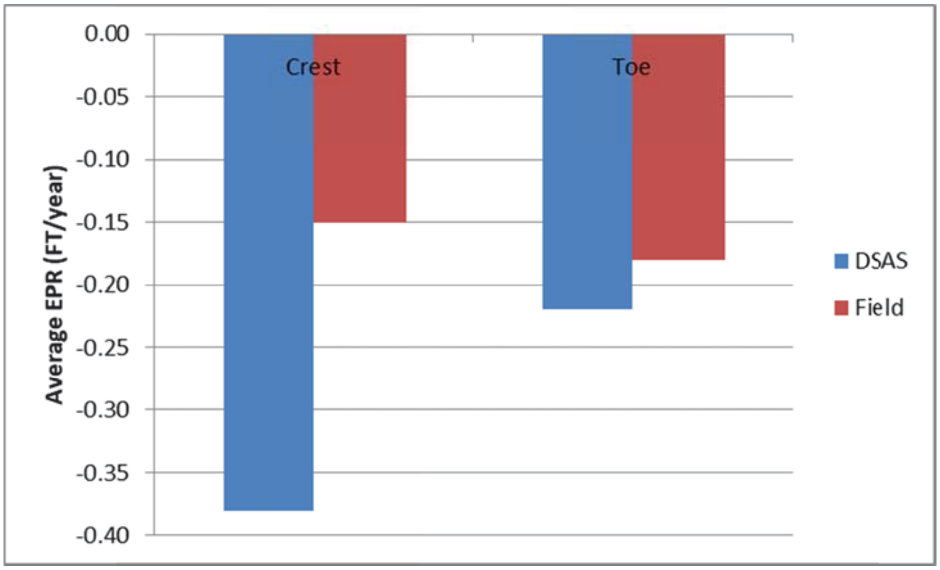

Figure 17. EPR as measured from the bluff crest and toe using DSAS and Field-based measurements.

Additional investigation into the number of years spanning the period of analysis was relevant. As described in the *Methods* section, due to the episodic nature of change along Puget Sound beaches, long-term bluff recession measurements were preferred as it has been suggested that longer term measurements are more accurate. This is because they capture more "change events", as well as periods in between change events when very little change occurs. These relationships were explored further together with the measurement method. The average long-term bluff recession rate decreased with the increased measurement period (Figure 18). Measurements that spanned 20–40 years appeared to have much greater long-term bluff recession rates than those measured from 40–60 years and 60+years, respectively. Results of these data explorations also showed that the difference in long-term bluff recession between the two measurement methods narrowed when evaluating over longer periods of time (Figure 18). These results suggest that longer-range, field-based measurements likely produce the most reliable calculated long-term bluff recession rates.

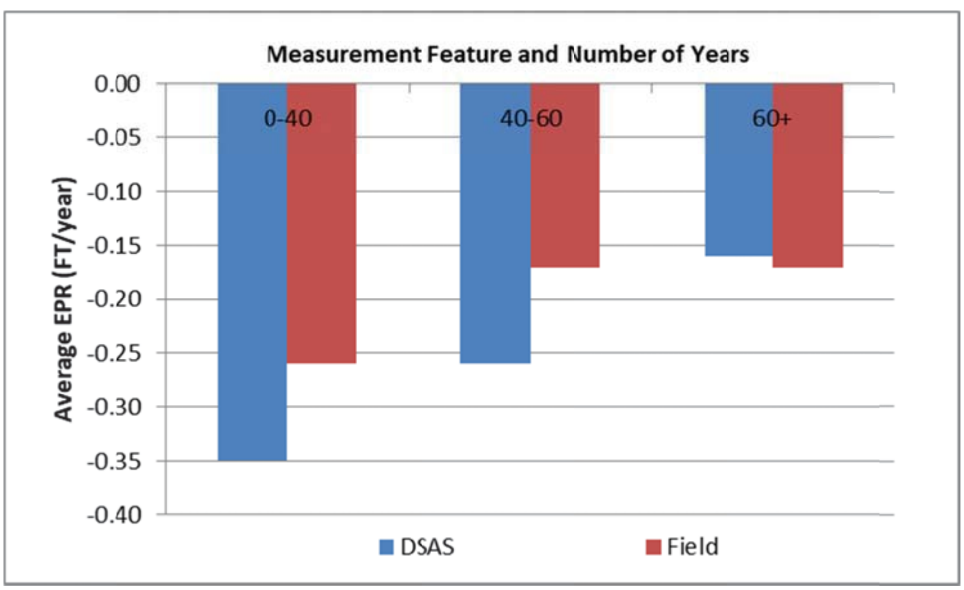

Figure 18. EPR as measured across number of years using DSAS and Field-based measurements.

Data Utility

The preferred regression model can be used with regional data and information in this report to provide an estimated range of historical long-term bluff recession rates in the Puget Sound region. There are many ways in which these data can be used; however users should be aware of the data's limitations, such as:

- Model output consider only the variables explored in this study and in reality many other factors contribute to bluff recession rates,
- Sources of error are carried forward in the estimated bluff recession rates,
- Estimates represent long-term bluff recession rates based on historical data and are not predictions of future bluff recession rates and do not account for additional bluff recession associated with sea level rise.

Model outputs can be viewed as an estimated range of long-term bluff recession rates possible for a given location, in the absence of site-specific measurement data. However, it is not recommended to use model estimates of bluff recession until additional exploration into the role of the measurement feature (i.e., bluff crest or toe) and the relationships with error and bias have been completed. Additional recommendations for using regional data with the regression model to estimate bluff recession rates are included in Appendix E.

Error, Uncertainty, and Bias

Long-term bluff recession measurements were conducted both in the field and using historical air photo analysis in GIS. The error and uncertainty associated with field-based measurements contrasts those made in GIS using historical imagery. The potential sources of error and uncertainty associated with both methods are described further below. Inherent uncertainty and bias is also associated with the selection of bluff recession measurements, discussed below.

Field-based Bluff Recession Measurement Error

Very little opportunity for error occurs within the field-based methods as the measurement locations were described in detail, had accompanying coordinates to help locate them, and were clearly marked with a USCGS marker. There is a chance that some survey monuments located on large intertidal boulders could have moved during storm events, as the movement of some beach boulders in high-wave-energy beaches has been noted in other unpublished CGS studies. However, there was very little evidence that this had happened for the sites used in this study. In most cases, survey markers were either found intact and upright, or were not found at all. Roughly 20% of the survey markers were lost and no historical bluff recession measure was made at those locations. In some cases, multiple measurements were referenced in the benchmark sheets. For these sites, the set of measurements were checked for general consistency prior to incorporating the average of the measurements.

Digital Bluff Recession Measurement Error

Digital bluff recession measurement methods employed are commonly conducted in the field of coastal geomorphology. Peer-reviewed research was referenced throughout the project, from the development of methods and protocols to the assessment of sources of bias, to optimize accuracy and to quantify error (Fletcher et al., 2003; Moore, 2000; Morton et al., 2004; Ruggerio et al., 2003; Ruggerio and List, 2009). The details associated with each of these efforts are further described below.

Optimizing Accuracy

Protocols were applied to limit additional error and optimize accuracy in the compilation and measurement of bluff recession rates, and include the following:

- Using the most landward shoreline proxy that can be interpreted with the greatest certainty
- Using the largest scale vertical aerial photos available (1:6,000-1:12,000)
- Using a single expert digitizer to the greatest extent possible
- Where different digitizers were used, all digitizing was reviewed by the lead coastal geomorphologist for consistency in interpretation of the shoreline proxy (typically bluff toe or bluff crest)
- Error associated with radial lens distortion in historical imagery was minimized to the greatest extent possible by selecting photos in which the measurement location was near the center of the image
- Ground control points were selected around the measurement location during georectification of historical imagery
- A minimum of 5–6 ground control points were placed surrounding the area of concern for each georeferenced historical air photo
- A maximum RMSE of 5.0 FT was applied to all georeferenced images
- Using DSAS to reduce error associated with change measurements
- Alongshore averages of change rates were used within each shoretype to nullify localized trends within a given reach of bluff
- Careful selection of sampled shoretypes to avoid potential sources of interference such as: bedrock promontories, rock outcrops directly off-shore, dramatic sediment supply loss in the drift cell, and significant armor within the subject shoreform.

Cumulative Error

Cumulative error calculations are commonly applied to quantify the various sources of error and uncertainty associated with digital shoreline change rates including historical bluff recession measurements (Ruggerio and List 2009, Fletcher et al. 2003, Ruggerio et al. 2003, Morton et al. 2004, Moore 2000). There are two different categories of uncertainty: positional and measurement. Positional uncertainty relates to all features and the exactitude of defining the true position of a given shoreline proxy in a given year. Positional uncertainty is reduced by measuring change from the most landward visible shoreline proxy. Measurement error relates to the operator-based manipulation of the map and photo products such as the orthorectification process, RMS values, pixel size, and the digitization of shoreline features (Fletcher et al. 2003). Measurement error was far more prevalent in this analysis.

Potential error associated with the historical air photo analysis was assessed using a formula developed for calculating the maximum level of error derived from this type of analysis by Morton et al. (2004). The equation (below), which integrates error values from various sources, was adapted slightly to account for the most relevant sources of error in this analysis. Calculations of both the lower and upper limits of the maximum potential error were conducted to better understand the range of error associated with these data (Table 10). The following sources of error were included in the equation: historical imagery, current imagery, LIDAR, and two different forms of digitizing error. Detailed descriptions of each source of error are shown in Table 9.

$$E_{sp} = \sqrt{E_p^2 + E_c^2} + E_l^2 + (E_{d1} + E_{d2})^2 + E_r^2$$

Table 9. Variables, data sources, and descriptions of each type of error included in the error analysis.

Variable	Data Source	Description
E_p	Historical imagery	The range of distortion resulting from the historical imagery. This value is less for digital imagery and is more closely associated with the resolution (pixel size) of the image.
E_c	Current imagery	High resolution, current orthorectified aerial images and LiDAR (see below) were used to digitize the current condition of the selected shoreline proxy. Modern imagery is typically both highly accurate and of higher resolution. Error value = 2x the pixel size (e.g. pixel size of 0.5 ft, 1 ft maximum error).
E_l	LIDAR	LiDAR was used to guide the delineation of the bluff crest. The positional error of LIDAR data was estimated by measuring 2x the pixel size (e.g. pixel size of 3 FT; 6 FT maximum error).
E_{d1}	Digitizing error (1)	This study used only georeferenced aerial photos and LiDAR to determine the location of digitized shoreline proxy (features), so an error value associated with pixel size as the determinant of placement and location of digitized lines is appropriate. Error values associated with pixel size of current imagery are already accounted for, so a weighted average of historical air photos pixel size was averaged to obtain the digitizer error value.
E_{d2}	Digitizing error (2)	To avoid introducing additional digitizing error all, digitized shoreline features were reviewed by an analyst. Digitizing error was measured by the original analyst by digitizing a bluff crest twice with considerable time between the two interpretation efforts, and then measuring the range of error between the two features locations. The time lapse between digitizing was designed to reduce to the ability of the digitizer to "remember" what they had digitized in the past. The difference in the position of the bluff crest ranged from 1.2 to 11.7 ft.
E_r	Rectificat ion error	The error is quantified in ArcGIS during the rectification process as the root mean square error (RMSE) and measures the misfit between points on the image being rectified to the orthorectified base map that was used. The reported RMSE was used in error analyses by Fletcher et al. (2003). For the purposes of this study, the average RMSE values for each rectified aerial photograph used to digitize shoreline proxy features were used to represent the rectification error value

Table 10. Variables, data sources, range of measured error, and cumulative error measures.

Variable	Data Source	Sources of Uncertainty	Low (FT)	High (FT)
E_p	Historical imagery	Historical image distortion	3.3	6.6
E_c	Current imagery	2008 orthorectified image	1	6
E_l	LiDAR	2x pixel size	1	6
E_{d1}	Digitizing error (1)	Weighted average pixel size	4.4	4.4
E_{d2}	Digitizing error (2)	Measured from heads up digitizing	0.5	11.7
E_r	Rectification error	Average RMSE for all images	1.4	5.0
Cumulative uncertainty			6.2	19.5
Minimum annualized uncertainty (80 years)			0.08	0.24
Mean annualized uncertainty (45.8)			0.14	0.43
Maximum annualized uncertainty (23 years)			0.27	0.84

Inherent Uncertainty and Bias

There is inherent uncertainty and bias embedded in the erosion rates measured in this study associated with the selection of measurement locations, the data referenced in the stratification structure, and the locations of the NGS monuments. Together this bias potentially skews the data towards the higher end of the range of erosion rates actually occurring in the Puget Sound region. Digital bluff recession measurements require a clearly identifiable bluff crest or toe, which is not commonly visible on heavily vegetated bluffs. Bluffs that are denuded of vegetation are typically receding at a faster pace than those covered with vegetation. Heavily forested bluffs, which likely represent some of the more slowly receding bluffs, are rarely selected for this type of bluff recession measure, as the bluff face cannot be reliably digitized.

Bluff stratigraphy data were referenced during the selection of new bluff measurement locations, to ensure that an adequate number of bluff measurements were made for each geology bin to have sufficient statistical power to detect a relationship with bluff recession rates. Stratigraphy data and bluff cross-sections commonly occur where the bluff face is free of vegetation, thereby exposing the strata that comprise the bluff. Similar to the measurement method issue described above, selecting sites with stratigraphy can bias results toward more rapidly receding bluffs.

The USCGS markers were placed strategically to facilitate mapping the topography of Puget Sound regional shores during early Euro-American settlement of the region. Many of these monuments were placed at locations that were visible from a distance, such as headlands and promontories that were used with other survey markers in triangulation to calculate distances from which the early maps were developed. There is bias in the selected locations of these survey markers, for even when they were placed within more sheltered areas, they were commonly more exposed sites that provided good line of sight to other monuments. Again, this likely leads to bluff recession rates being skewed toward more quickly receding bluffs; users of these data should be mindful of that complexity.

Further Research

The objective of this study was to compile a bluff recession database for the Puget Sound region, from which the range of rates and drivers of bluff recession throughout the region could be better understood. This database represents a robust foundation that can be built upon in several different ways, as outlined below.

Additional Measurements

Additional long-term bluff recession measurement locations and rates could be incorporated into the dataset to augment the existing data and address spatial gaps in coverage. Additional bluff recession measurements from existing locations could be added to better understand both longer and shorter-term trends in bluff recession. The viability of using additional historical measurements of bluff recession could be evaluated, since these are known to be of insufficient accuracy in some locations. Reliable areas of historical shore mapping from T-sheets could be integrated with relatively little effort. This would extend the measurement period substantially and could provide useful long-term data, but may not be appropriate for every area due to accuracy limitations.

Temporal Analysis

Decadal-scale bluff recession trends could be explored by conducting additional measurements from a subset of sites using aerial photography from the 1980s, 1990s, and 2000s. Those trends could be analyzed and compared across the subset of sites and perhaps paired with storm event data. This higher resolution analysis could incorporate higher resolution geology, wave data, beach topography, substrate, and sediment transport rates. These data would also be useful for examining whether recession rates have changed over time.

Causation and Modeling

Several variables analyzed in this study show initial relationships to bluff recession rates and are available Sound-wide, making predictive modeling more widely accessible. Additional research is needed to further advance the model's application and establish a greater understanding of specific ways these variables relate to recession rates across the Sound. Higher resolution analysis of the variables included in the predictive model, in addition to new variables, could help to explain additional variability in bluff recession rates. As mentioned in the *Methods* section, all bluff recession measurements were made from unarmored bluffs. Additional research on the rate at which armored bluff crests recede as compared to unarmored bluffs could provide valuable insight into the degree to which armor slows bluff recession.

Additional Shoreforms

Although not included in this study, low-elevation shores, commonly classified as barrier beaches or accretion shoreforms in the region, exhibit substantial variability in their change rates and morphological patterns. Limited preliminary analyses have been conducted to explore the drivers of change on these shores, but additional work could be done to conduct more systematic change analyses to determine the dominant drivers of change for these shores.

Conclusion

The project database can easily expanded over time to include these topics (adding bluff recession measurements, replicating measurements from old sites but at new temporal scales, and including change rates from other shoretypes and potential drivers of shore change). Greater understanding of the rates and drivers of shoreline change in the Puget Sound region can inform better management, which can improve conditions for nearshore habitats, processes, and the larger nearshore ecosystem as a whole. Better understanding of historical bluff recession rates can also be used to characterize the degree to which bluff erosion is likely to accelerate due to climate change. The greater the understanding of past trends, the greater the capacity will be for projecting future trends. All of this enables improved management and preservation of coastal ecosystem processes, habitats, and the many other qualities for which the Puget Sound region is so valued.

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Map Figures

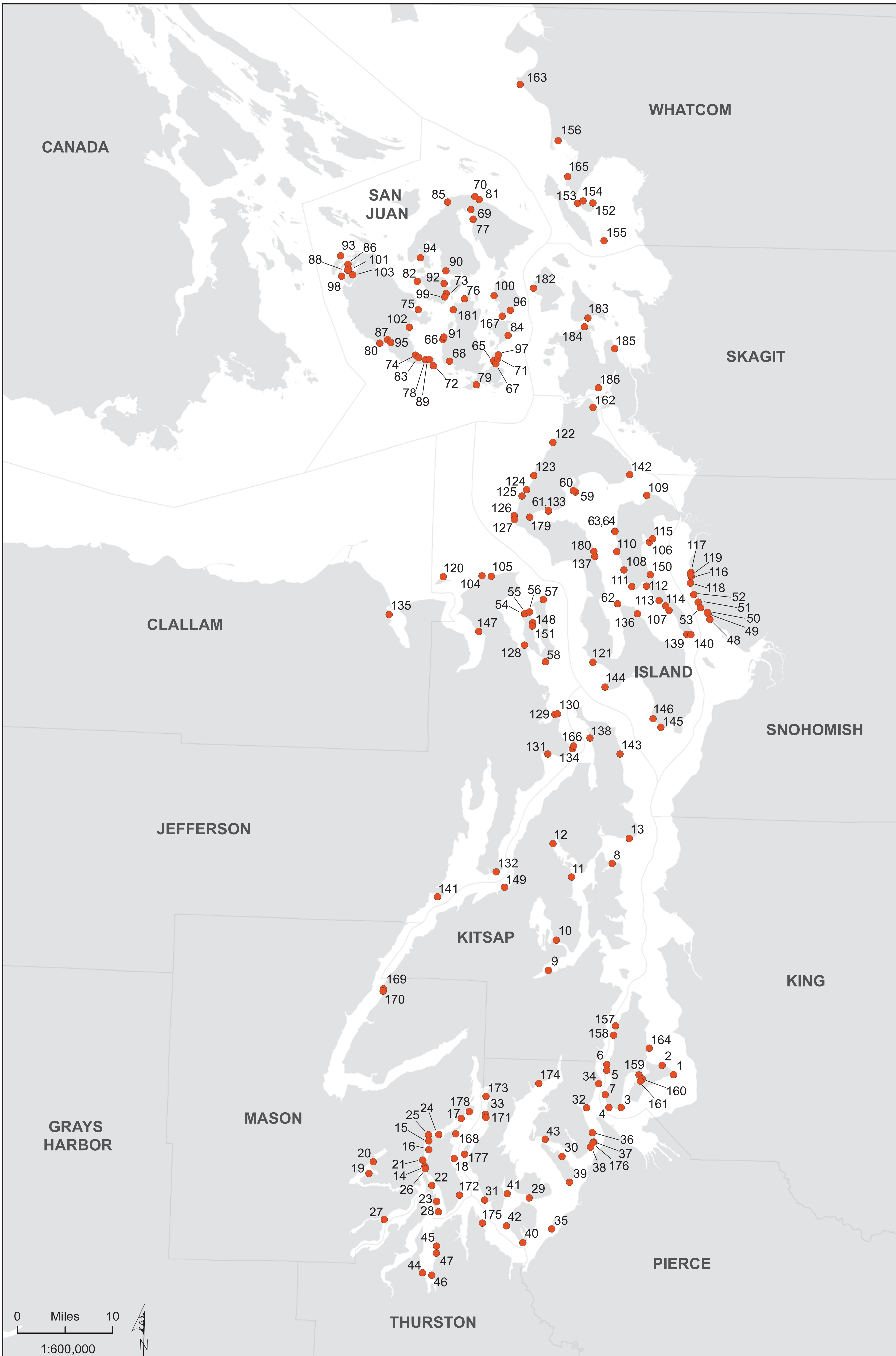

Figure 2. Bluff recession point locations. Labels correspond to the unique identifiers in Appendix A.

ESRP Learning Project - Long-Term Bluff Recession Rates in Puget Sound

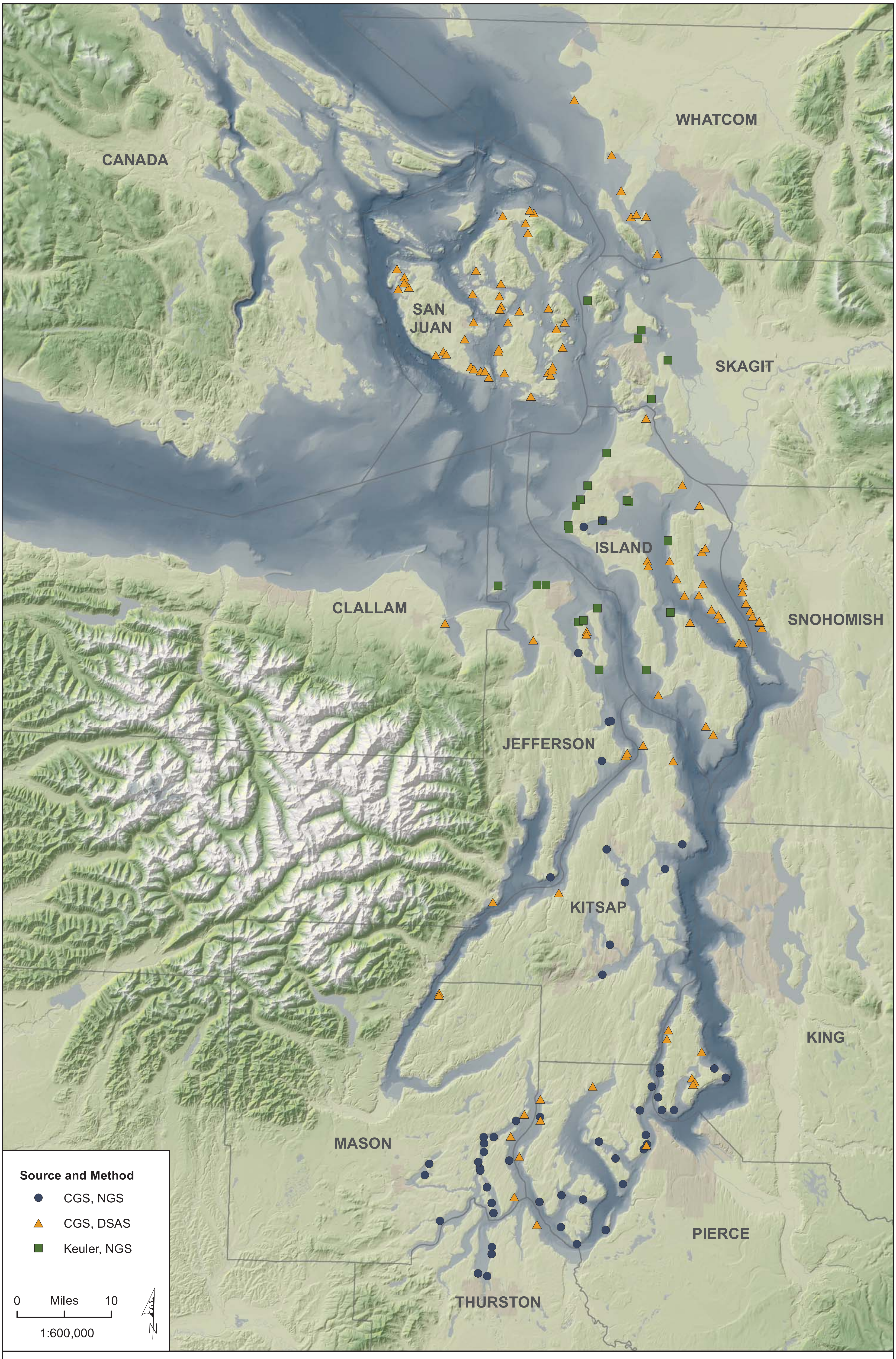

Figure 3. Recession rate locations by data source and method of measurement.
NGS: National Geodetic Survey monuments; DSAS: Digital Shoreline Analysis Systems.
ESRP Learning Project - Long-Term Bluff Recession Rates in Puget Sound

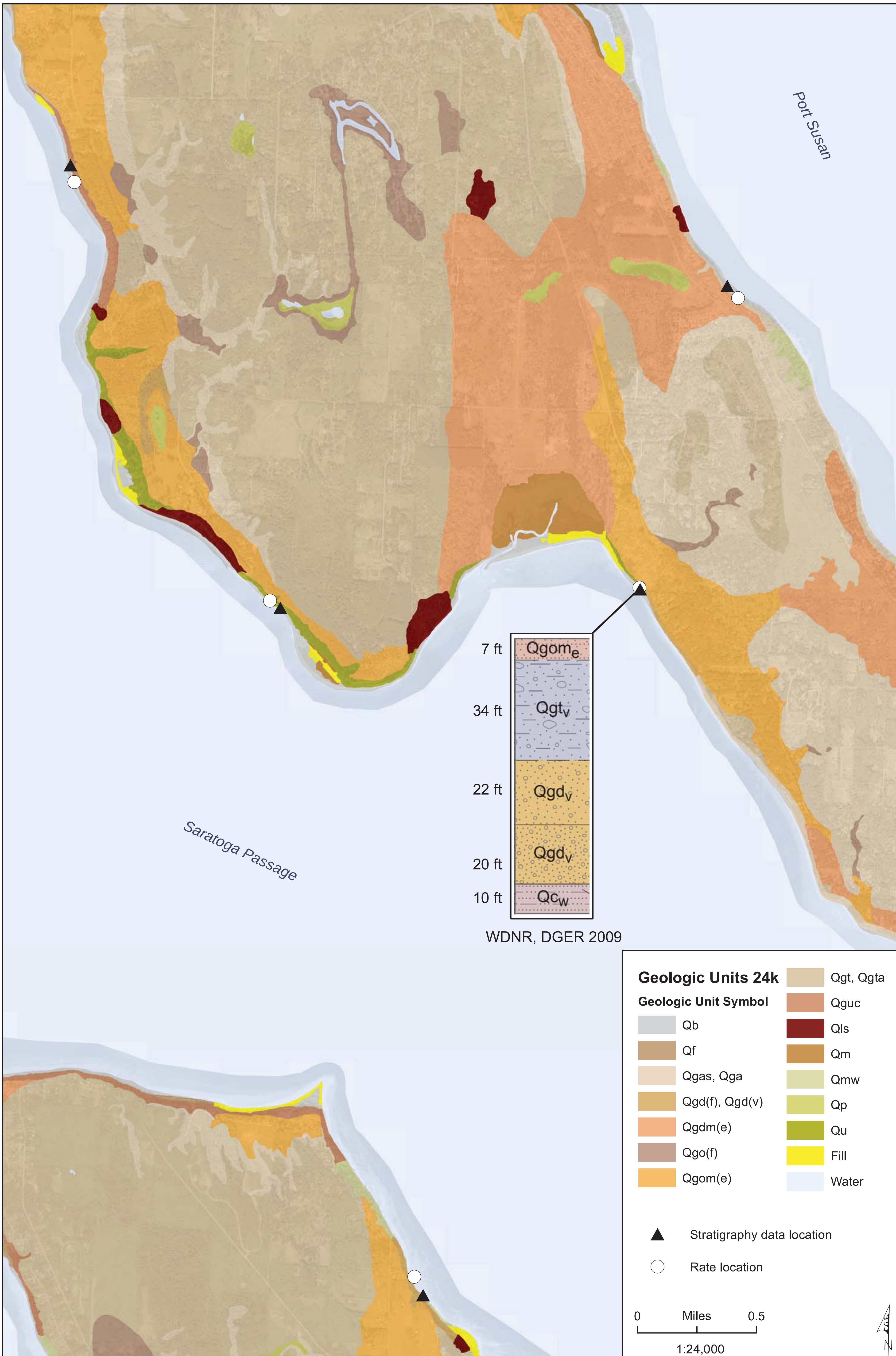

Figure 10. Surface geology and stratigraphic column locations of southern Camano and Whidbey Islands, 1:24,000 scale. Geology mapping from the Washington Department of Natural Resources, Division of Geology and Earth Resources, November 2016.
ESRP Learning Project - Long-Term Bluff Recession Rates in Puget Sound

COASTAL GEOLOGIC SERVICES

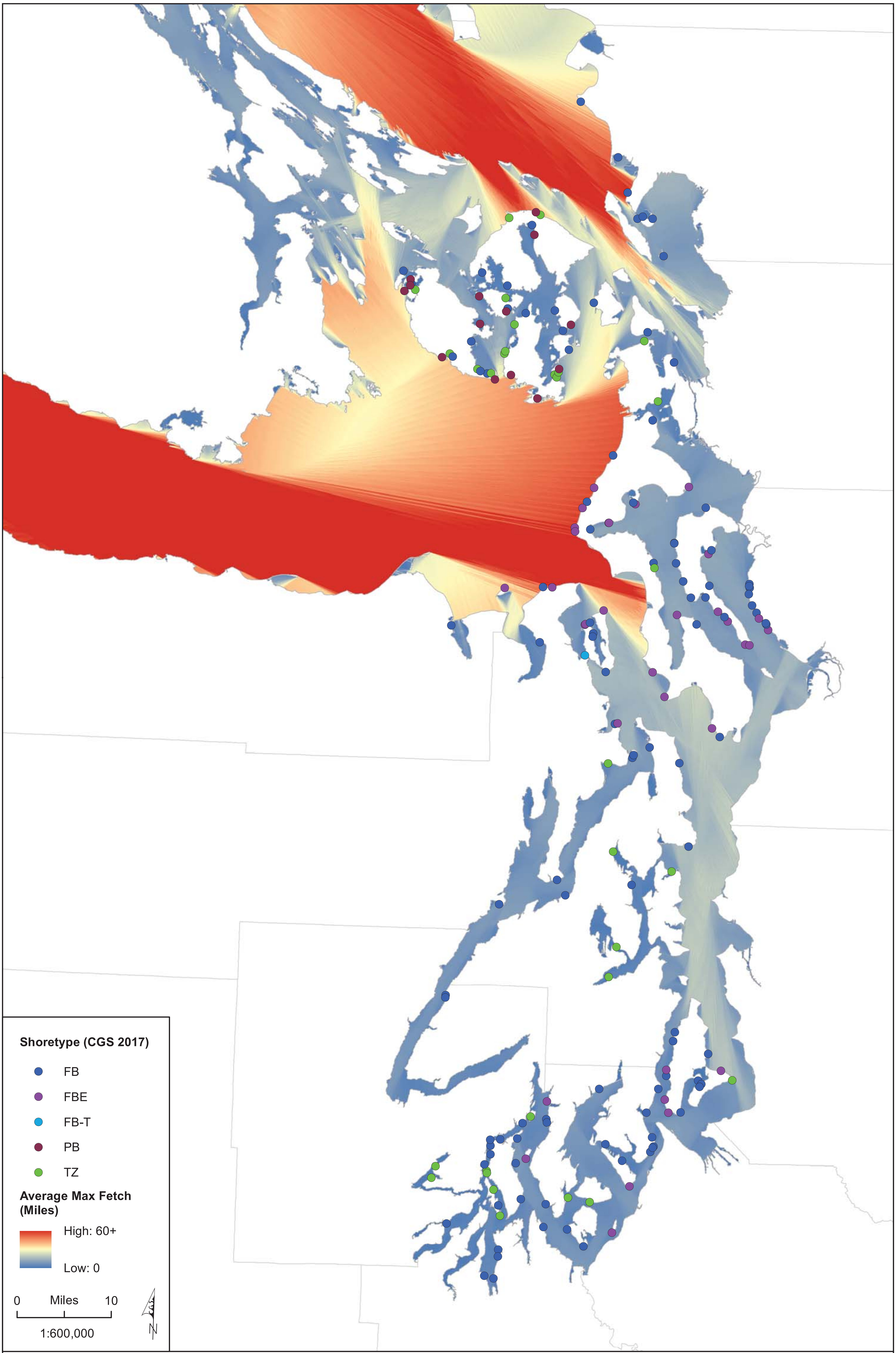

Figure 12. Average maximum fetch and geomorphic shoretype.

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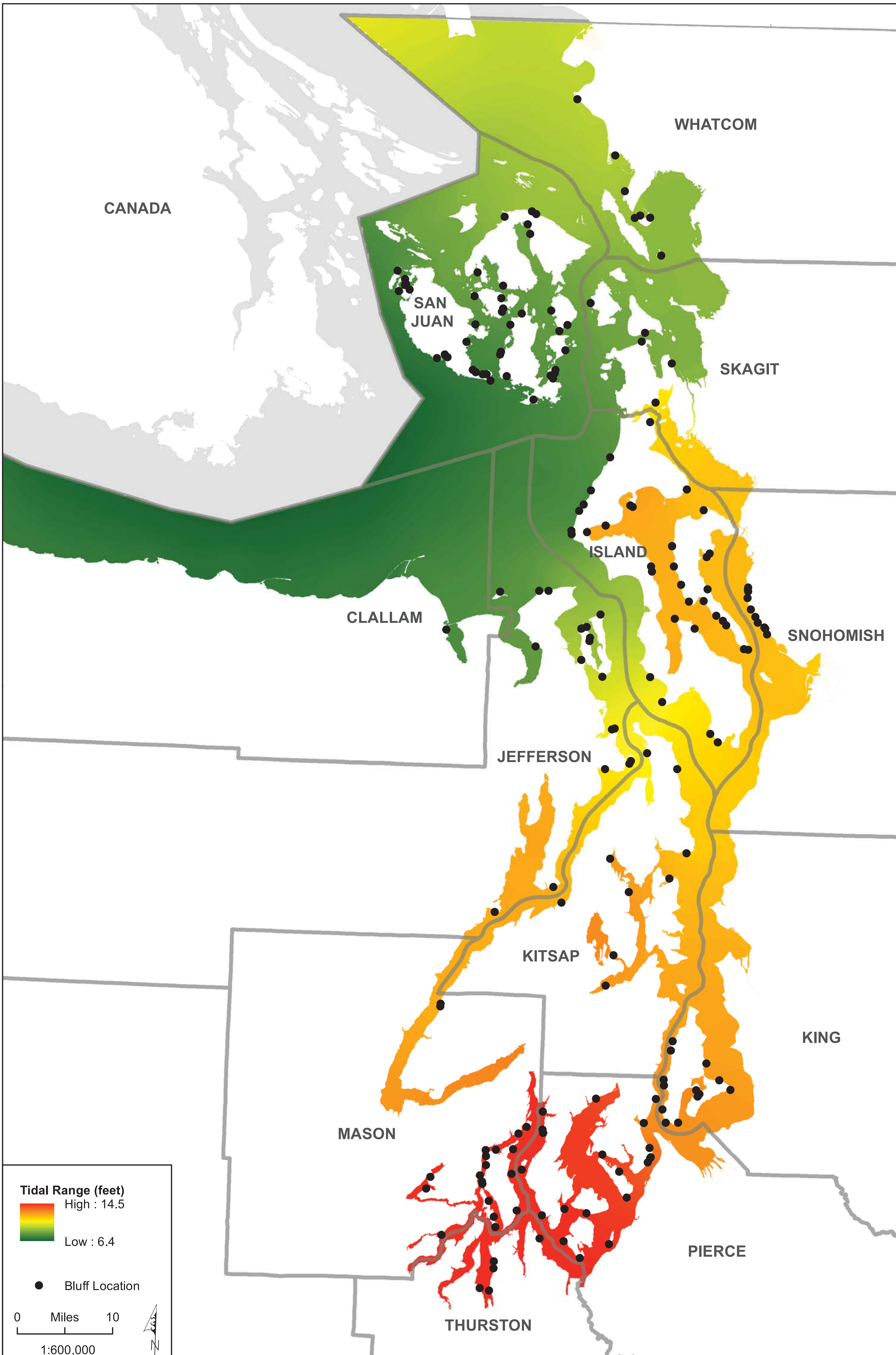

Figure 14. Maximum tidal range of Puget Sound and the Northwest Straits.

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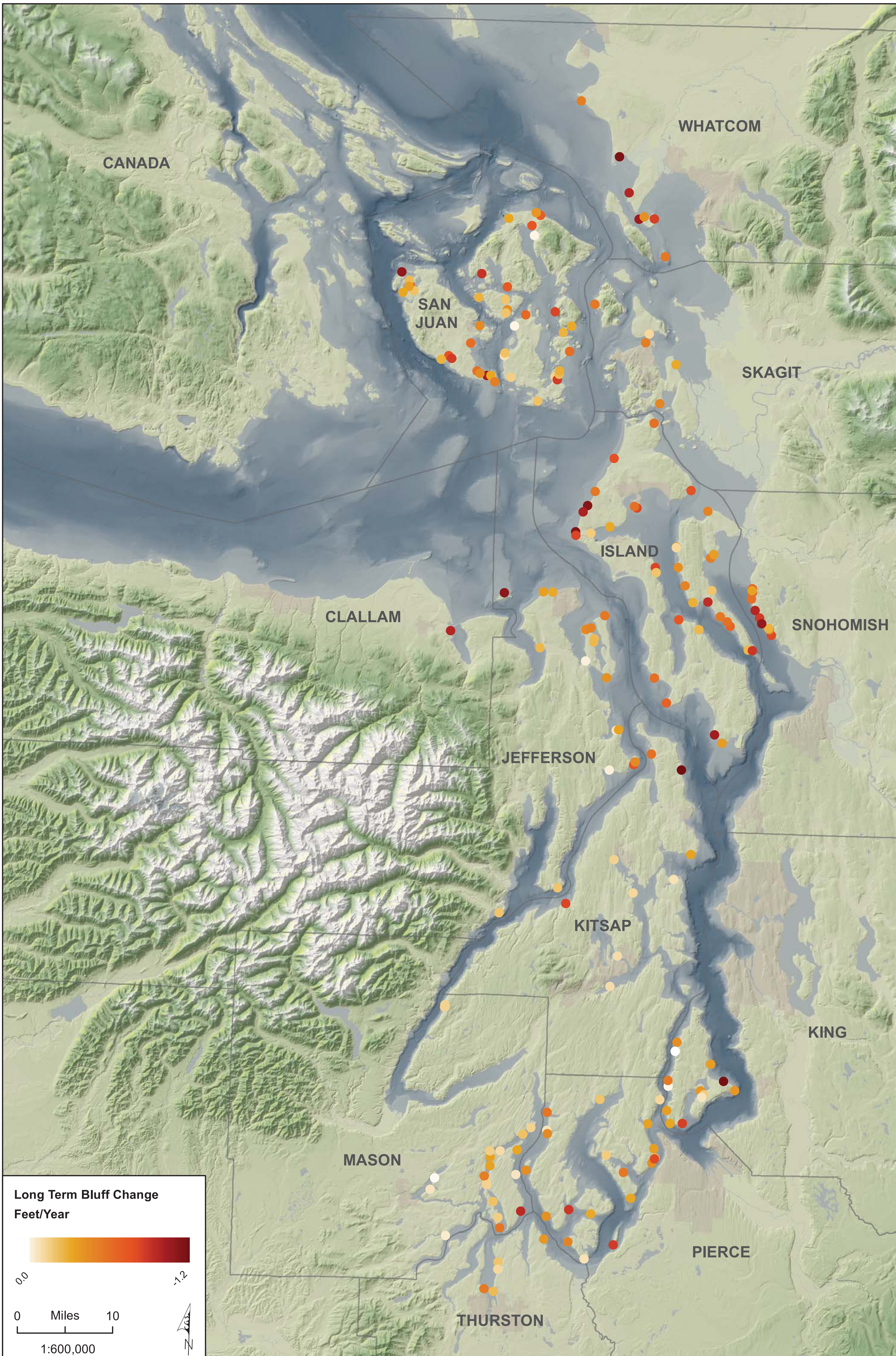

Figure 15. Bluff recession estimate locations and change rates in feet per year.

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Appendices

Appendix A — Data Compilation for All Sites

Map Label	Rate Point ID	Method	EPR (FT/YR)	Years	Latitude	Tide Range (FT MHHW-MLLW)	Feature	Shoretype	Orientation	Finlayson Fetch (Miles)	Bluff Height	Surface Geology Units*	Surface Geology Bin	Bluff Toe Geology Bin	Perm/ Imperm	Drift Cell Percent Downdrift
1	11	CGS Field	-0.25	52	47.38599	11.73	Bluff Toe	TZ	S	8.11	20	Qpf	2	2	1	4%
2	12	CGS Field	-1.19	52	47.40004	11.70	Bluff Toe	FBE	N	17.17	150	Qwbc (1:24k)	3	3	ND	43%
3	14	CGS Field	-0.5	52	47.33441	11.92	Bluff Toe	FB	N	7.22	30	Qls, Qga, Qgt 100k	4	3	ND	97%
4	15	CGS Field	-0.21	40	47.33375	11.93	Bluff Toe	FBE	S	6.14	80	Qgpc, Qgt 100k	2	2	ND	52%
5	16	CGS Field	-0.01	43	47.39032	11.85	Bluff Toe	FB	S	5.47	130	Qpog(c), Qpo(f), Qva, Qvt	2	2	0	12%
6	17	CGS Field	-0.32	82	47.39918	11.82	Bluff Toe	FBE	N	4.60	80	Qpog(t), Qpo(f), Qpog, Qva, Qvt	2	2	1	32%
7	18	CGS Field	-0.23	52	47.35358	11.93	Bluff Toe	FBE	N	4.03	200	Qgpc, Qgp, Qga, Qgt 100k	2	2	ND	77%
8	20	CGS Field	-0.07	60	47.70472	11.40	Bluff Toe	TZ	N	3.01	13	Qvt	1	1	1	69%
9	21	CGS Field	-0.08	51	47.53976	11.73	Bluff Toe	TZ	N	3.98	10	Qa, Qgu 100k	4	4	ND	0%
10	23	CGS Field	-0.08	51	47.58629	11.91	Bluff Toe	TZ	S	0.97	30	Qgd 100k	3	3	ND	27%
11	24	CGS Field	-0.1	71	47.68262	11.71	Bluff Toe	FB	N	3.66	210	Qls, Qvlc, Qve	4	2	ND	43%
12	26	CGS Field	-0.11	47	47.73273	11.73	Bluff Toe	TZ	S	2.09	10	Qgt, Qga 100k	1	3	ND	25%
13	27	CGS Field	-0.22	85	47.74365	10.98	Bluff Toe	FB	S	15.86	36	Qvt	1	1	ND	86%
14	30	CGS Field	-0.11	58	47.23639	14.27	Bluff Toe	TZ	S	1.64	10	Qgof, Qgt	4	2	ND	13%
15	36	CGS Field	-0.22	49	47.27527	14.16	Bluff Toe	FB	S	2.22	20	Qpu	3	3	1	27%
16	37	CGS Field	-0.22	58	47.26186	14.20	Bluff Toe	FB	S	1.88	20	Qpu	3	3	1	60%
17	38	CGS Field	-0.15	49	47.31119	14.08	Bluff Toe	FB	S	4.17	20	Qgt	1	1	ND	54%
18	43	CGS Field	-0.06	82	47.24950	13.95	Bluff Toe	FB	S	8.34	20	Qgt	1	1	ND	51%
19	44	CGS Field	-0.06	43	47.22315	14.21	Bluff Toe	TZ	N	1.70	30	Qgt	1	1	ND	25%
20	46	CGS Field	0.01	43	47.24104	14.21	Bluff Toe	TZ	N	1.54	50	Qga	4	1	ND	38%
21	47	CGS Field	-0.31	80	47.24613	14.24	Bluff Toe	FB	S	2.09	10	Qgt	1	1	ND	33%
22	48	CGS Field	-0.15	80	47.20756	14.29	Bluff Toe	TZ	N	2.23	10	Qgt	1	2	ND	70%
23	49	CGS Field	-0.12	80	47.18354	14.29	Bluff Toe	FB	N	1.76	15	Qgas, Qgt	4	1	ND	28%
24	51	CGS Field	-0.08	49	47.28530	14.13	Bluff Toe	FB	N	3.06	20	Qpu	3	3	1	65%
25	52	CGS Field	-0.12	80	47.28447	14.15	Bluff Toe	FB	S	3.04	50	Qpu	3	3	1	92%
26	53	CGS Field	-0.11	58	47.23300	14.28	Bluff Toe	TZ	S	1.36	20	Qgof, Qgt	4	1	ND	15%
27	54	CGS Field	-0.05	80	47.15350	14.50	Bluff Toe	FB	S	2.32	50	Qpg	2	1	0	93%
28	55	CGS Field	-0.35	92	47.16800	14.31	Bluff Crest	TZ	S	3.25	10	Qgt	1	1	ND	99%
29	57	CGS Field	-0.2	49	47.19297	13.55	Bluff Toe	TZ	S	4.14	30	Qgt	1	1	ND	76%
30	58	CGS Field	-0.33	81	47.25772	13.12	Bluff Toe	FB	N	3.13	20	Qgp, Qgt 100k	1	2	ND	18%
31	60	CGS Field	-0.26	50	47.18781	14.10	Bluff Toe	FB	S	5.65	80	Qls	4	1	1	96%
32	61	CGS Field	-0.22	92	47.33271	12.00	Bluff Toe	FB	S	7.35	280	Qgpc, Qgt 100k	2	1	0	92%
33	63	CGS Field	-0.06	37	47.31820	14.09	Bluff Toe	FB	N	5.52	50	Qu, Qgt	1	1	ND	69%
34	64	CGS Field	-0.1	50	47.36956	11.91	Bluff Toe	FB	S	4.35	130	Qgpc, Qgas, Qgt 100k	2	1	0	15%
35	65	CGS Field	-0.52	36	47.14696	13.49	Bluff Toe	FBE	S	5.27	170	Qpg, Qps, Qu, Qgo	2	1	1	100%
36	66	CGS Field	-0.23	52	47.29498	12.29	Bluff Toe	FB	N	5.36	200	Qls, Qgt 100k	4	2	ND	27%
37	68	CGS Field	-0.16	81	47.28089	12.51	Bluff Toe	FB	S	5.94	120	Qgpc, Qgt 100k	2	2	0	11%
38	69	CGS Field	-0.27	36	47.27279	12.60	Bluff Toe	FB	S	6.22	100	Qgpc, Qga 100k	2	2	ND	37%
39	70	CGS Field	-0.21	36	47.21870	13.25	Bluff Toe	FBE	S	7.24	160	Qgo, Qgd, Qgt 100k	4	1	ND	95%
40	71	CGS Field	-0.07	39	47.12459	13.67	Bluff Toe	FB	S	4.58	30	Qps, Qgof	4	2	ND	79%
41	74	CGS Field	-0.53	50	47.19877	13.65	Bluff Toe	TZ	S	4.53	20	Qls, Qgt	1	2	ND	32%
42	75	CGS Field	-0.3	36	47.14972	13.91	Bluff Toe	FB	S	4.71	90	Qpg, Qgt	2	1	ND	38%
43	76	CGS Field	-0.13	81	47.28270	13.31	Bluff Toe	FB	S	4.29	30	Qgt	1	1	ND	13%
44	78	CGS Field	-0.32	41	47.07475	14.51	Bluff Toe	FB	N	5.03	70	Qls, Qpf, Qga, Qgt	4	2	1	65%
45	81	CGS Field	-0.14	40	47.11591	14.44	Bluff Toe	FB	S	3.51	40	Qpg, Qps, Qgof	2	2	1	94%
46	82	CGS Field	-0.16	41	47.07123	14.53	Bluff Toe	FB	S	3.22	80	Qps, Qgos	2	2	1	98%
47	84	CGS Field	-0.1	40	47.10518	14.47	Bluff Toe	FB	N	3.37	100	Qpg, Qps, Qgos	2	2	0	17%
48	256	DSAS	-0.47	56	48.07936	11.16	Bluff Crest	FBE	S	8.58	190	Qgas, Qgt 100k	4	4	ND	84%
49	257	DSAS	-0.28	56	48.08792	11.17	Bluff Crest	FB	S	7.62	155	Qgas, Qgt 100k	4	4	ND	77%

*Surface geology units mapped around bluff site at 1:24k scale or 1:100k scale. A significant amount of case-by-case analysis went into assigning bins for each bluff; some units may not fit into bins as shown in Table 2.

Map Label	Rate Point ID	Method	EPR (FT/YR)	Years	Latitude	Tide Range (FT MHHW-MLLW)	Feature	Shoretype	Orientation	Finlayson Fetch (Miles)	Bluff Height	Surface Geology Units*	Surface Geology Bin	Bluff Toe Geology Bin	Perm/ Imperm	Drift Cell Percent Downdrift
50	258	DSAS	-0.18	56	48.08975	11.18	Bluff Crest	FB	S	7.67	105	Qls, Qb, Qgas 100k	4	4	ND	75%
51	260	DSAS	-0.52	38	48.10545	11.20	Bluff Crest	FB	S	7.91	320	Qgas 100k	4	4	ND	58%
52	261	DSAS	-0.68	38	48.11669	11.21	Bluff Crest	FB	S	10.78	300	Qgas 100k	4	4	ND	48%
53	263	DSAS	-0.87	38	48.09691	11.19	Bluff Crest	FBE	S	9.46	270	Qgas 100k	4	4	ND	66%
54	269	Keuler Field	-0.2	ND	48.08054	8.70	ND	FBE	N	8.38	125	Qga, Qgt 100k	4	4	0	95%
55	270	Keuler Field	-0.29	ND	48.08122	8.70	ND	FBE	N	8.82	125	Qga, Qgt 100k	4	4	0	97%
56	271	Keuler Field	-0.3	ND	48.08382	8.66	ND	FB	N	1.95	25	Qga 100k	4	4	ND	4%
57	272	Keuler Field	-0.33	ND	48.10307	8.70	ND	FBE	N	29.92	100	Qga, Qgt 100k	4	4	ND	68%
58	273	Keuler Field	-0.26	ND	48.00867	9.46	ND	FB	S	15.33	75	Qguc, Qgt 100k	4	4	1	83%
59	274	Keuler Field	-0.49	ND	48.26776	11.54	ND	FBE	S	10.60	30	Qgt(v), Qgdm(ec)	3	3	1	91%
60	275	Keuler Field	-0.36	ND	48.27006	11.54	ND	FB	S	9.80	40	Qgics e	3	3	ND	70%
61	276	Keuler Field	-0.21	ND	48.23808	11.52	ND	FBE	S	7.36	55	Qgdm e	3	2	0	46%
62	278	Keuler Field	-0.43	ND	48.09957	11.33	ND	FBE	N	11.70	10	Qgt(v)	1	1	ND	83%
63	280	Keuler Field	-0.23	ND	48.20996	11.42	ND	FB	N	7.39	200	Qguc, Qgt(v)	1	2	1	44%
64	281	Keuler Field	-0.1	ND	48.20929	11.42	ND	FB	N	7.36	200	Qguc, Qgt(v)	1	2	1	44%
65	287	DSAS	-0.11	49	48.46368	7.67	Bluff Toe	TZ	S	1.68	15	Qgdm e 100k	3	3	ND	99%
66	289	DSAS	-0.07	49	48.49353	7.46	Bluff Toe	TZ	N	10.63	30	Qva, Qvt	4	4	0	60%
67	291	DSAS	-0.52	49	48.45943	7.63	Bluff Crest	TZ	N	8.81	15	Qb, Qgt 100k	1	1	ND	57%
68	293	DSAS	-0.12	32	48.46077	7.27	Bluff Toe	PB	S	27.07	25	Qvrmd	3	3	ND	NAD
69	295	DSAS	-0.43	49	48.69232	8.09	Bluff Crest	FB	S	3.25	60	Qvt, Qva, Qns	1	2	1	60%
70	298	DSAS	-0.25	49	48.71225	8.70	Bluff Toe	PB	N	40.02	30	Kn(nc), Km(nh), Qgom e 100k	3	3	ND	NAD
71	301	DSAS	-0.16	49	48.46751	7.63	Bluff Toe	TZ	S	9.96	20	Qgdm e 100k	3	3	ND	22%
72	304	DSAS	-0.31	49	48.45327	7.17	Bluff Toe	PB	S	25.20	25	Qvrmd	3	1	1	NAD
73	305	DSAS	-0.26	49	48.56326	7.68	Bluff Toe	FB	S	2.48	20	Qtf, Qpfn, Qva	2	2	1	78%
74	308	DSAS	-0.36	49	48.46874	7.35	Bluff Toe	TZ	N	6.58	15	Qvrmd	3	3	ND	52%
75	309	DSAS	-0.28	49	48.53800	7.72	Bluff Toe	PB	N	3.32	15	Br, Qvd	1	1	ND	NAD
76	310	DSAS	-0.38	49	48.55646	7.76	Bluff Crest	FB	N	2.43	60	Qva, Qvt	4	4	0	62%
77	318	DSAS	-0.01	49	48.67757	8.08	Bluff Toe	PB	N	2.17	15	pDi(t) 100k	1	1	ND	NAD
78	319	DSAS	-0.74	49	48.46229	7.34	Bluff Crest	FB	N	6.43	75	Qvrmo	3	3	ND	99%
79	320	DSAS	-0.15	49	48.42621	7.38	Bluff Toe	PB	N	3.95	20	KJm(ll), Jvb(l), Qgdme 100k	3	3	ND	NAD
80	321	DSAS	-0.18	49	48.48482	6.98	Bluff Toe	PB	S	7.97	20	Br	1	1	ND	NAD
81	333	DSAS	-0.41	49	48.70814	8.70	Bluff Toe	TZ	N	18.19	40	Km(nh), Qgome 100k	3	3	ND	21%
82	334	DSAS	-0.18	49	48.58061	7.89	Bluff Toe	PB	S	3.36	20	Br	1	1	ND	NAD
83	337	DSAS	-0.28	49	48.46533	7.34	Bluff Crest	FB	N	6.53	35	Qvrmo	3	4	1	67%
84	338	DSAS	-0.37	49	48.50255	7.71	Bluff Toe	FB	S	17.26	65	Qgt 100k	1	1	ND	88%
85	341	DSAS	-0.21	49	48.70237	8.53	Bluff Toe	TZ	S	25.27	25	Qgd 100k	3	3	ND	64%
86	349	DSAS	-0.16	49	48.60307	7.58	Bluff Toe	PB	S	0.80	15	pDi 100k	1	1	ND	NAD
87	351	DSAS	-0.44	49	48.49085	6.98	Bluff Crest	TZ	S	22.66	30	Qvrms	3	3	ND	11%
88	353	DSAS	-0.23	49	48.59402	7.61	Bluff Toe	PB	S	1.42	15	JTRmc, Qgt 100k	1	1	ND	NAD
89	359	DSAS	-0.21	49	48.46261	7.33	Bluff Toe	TZ	N	4.56	15	Br	1	1	ND	6%
90	363	DSAS	-0.42	32	48.59807	7.87	Bluff Toe	FB	S	1.38	35	Qvt, Br	1	1	0	46%
91	369	DSAS	-0.15	49	48.49741	7.48	Bluff Toe	TZ	N	5.31	25	Qva, Qvt	4	4	1	53%
92	380	DSAS	-0.14	49	48.57876	7.84	Bluff Toe	TZ	S	1.28	15	Br, Qvd	1	1	ND	19%
93	384	DSAS	-0.93	49	48.61566	7.55	Bluff Crest	FB	N	11.00	55	JTRmc 100 k	1	1	ND	71%
94	385	DSAS	-0.55	49	48.61703	7.96	Bluff Crest	FB	S	2.41	50	Br, Qvt	1	4	0	40%
95	386	DSAS	-0.52	49	48.48668	6.98	Bluff Crest	FB	S	33.67	35	Ql, Br, Qvrms	4	4	0	50%
96	391	DSAS	-0.2	49	48.54107	7.86	Bluff Toe	PB	S	7.65	25	Ji(f), Qgt 100k	1	1	0	NAD
97	398	DSAS	-0.19	49	48.47254	7.65	Bluff Toe	PB	N	8.52	15	Jvb(f) 100k	1	1	ND	NAD
98	405	DSAS	-0.21	49	48.58484	7.47	Bluff Toe	PB	S	24.64	15	JTRmc, Qgt 100k	1	1	ND	NAD
99	407	DSAS	-0.14	49	48.55824	7.67	Bluff Toe	PB	S	2.85	20	Br	1	1	ND	NAD

Map Label	Rate Point ID	Method	EPR (FT/YR)	Years	Latitude	Tide Range (FT MHHW-MLLW)	Feature	Shoretype	Orientation	Finlayson Fetch (Miles)	Bluff Height	Surface Geology Units*	Surface Geology Bin	Bluff Toe Geology Bin	Perm/ Imperm	Drift Cell Percent Downdrift
100	411	DSAS	-0.49	49	48.56227	7.91	Bluff Crest	FB	S	5.04	65	Qgd, Ji(f) 100k	1	1	1	76%
101	412	DSAS	-0.39	49	48.59607	7.61	Bluff Toe	FB	S	0.97	20	JTRmc, Qgt 100k	1	1	ND	93%
102	430	DSAS	-0.37	49	48.51083	7.40	Bluff Crest	FB	S	3.76	30	Br, Qvd	1	1	ND	22%
103	433	DSAS	-0.15	49	48.58737	7.61	Bluff Toe	TZ	S	0.45	20	pPMsh 100k	1	1	ND	75%
104	434	Keuler Field	-0.23	ND	48.13642	7.81	ND	FB	N	46.09	90	Qb, Qguc, Qgdme	4	4	1	71%
105	435	Keuler Field	-0.2	ND	48.13654	7.94	ND	FBE	N	58.04	270	Qls, Qguc, Qgt	4	4	1	52%
106	436	DSAS	-0.31	56	48.19431	11.24	Bluff Crest	FBE	S	11.99	140	Qb, Qgas(v), Qgt(v)	4	4	ND	63%
107	437	DSAS	-0.39	46	48.09145	11.28	Bluff Crest	FBE	S	7.12	145	Qb, Qguc, Qgdme	4	2	1	81%
108	438	DSAS	-0.3	46	48.15140	11.36	Bluff Crest	FB	S	7.27	175	Qb, Qguc, Qgome	4	1	1	78%
109	439	DSAS	-0.3	47	48.26549	11.17	Bluff Crest	FB	N	9.06	110	Qga(v), Qgt(v), Qgdm(ec)	4	4	1	71%
110	440	DSAS	-0.27	48	48.17893	11.41	Bluff Crest	FB	S	8.31	110	Qguc, Qgdme, Qgome	4	4	ND	62%
111	441	DSAS	-0.19	46	48.12626	11.33	Bluff Crest	FB	S	4.08	155	Qgou, Qgom e (1:24k, juniper)	3	4	0	94%
112	442	DSAS	-0.64	45	48.12762	11.31	Bluff Crest	FB	S	6.28	105	Qc w, Qgom e	3	3	1	13%
113	443	DSAS	-0.33	37	48.10589	11.29	Bluff Crest	FBE	S	7.51	155	Qb, Qgas(v), Qgdme	4	4	ND	53%
114	444	DSAS	-0.36	46	48.09809	11.28	Bluff Crest	FB	S	7.00	135	Qgas(v), Qgome	4	4	ND	70%
115	445	DSAS	-0.23	45	48.20006	11.24	Bluff Crest	FB	S	11.71	135	Qgas(v), Qgt(v)	4	4	ND	92%
116	446	DSAS	-0.39	56	48.14371	11.24	Bluff Crest	FB	S	6.25	175	Qgas, Qgt 100k	4	4	1	26%
117	447	DSAS	-0.4	56	48.14965	11.23	Bluff Crest	FB	S	6.23	190	Qgt 100k	1	1	1	21%
118	448	DSAS	-0.36	56	48.13381	11.23	Bluff Crest	FB	S	5.46	185	Qguc, Qgt 100k	4	4	ND	34%
119	449	DSAS	-0.22	56	48.14647	11.23	Bluff Crest	FB	N	6.46	165	Qgas, Ggt 100k	4	4	1	24%
120	450	Keuler Field	-0.98	ND	48.13321	7.61	ND	FBE	N	32.13	125	Qguc 100k	4	4	1	59%
121	452	Keuler Field	-0.36	ND	48.01013	9.73	ND	FBE	S	11.68	75	Qgt(v), Qgics(f)	3	1	1	28%
122	454	Keuler Field	-0.46	ND	48.34202	7.62	ND	FB	N	51.88	35	Qb, Qgdm(ec), Qgdm(ed)	3	3	0	36%
123	455	Keuler Field	-0.33	ND	48.29131	7.44	ND	FBE	N	52.42	230	Qc(wcf), Qc(wc), Qc(o), Qgt(v), Qd	4	2	1	65%
124	456	Keuler Field	-1.05	ND	48.26950	7.42	ND	FB	N	50.64	55	Qgt(v), Qgdm(ed), Qgose	3	3	ND	76%
125	457	Keuler Field	-0.72	ND	48.25961	7.44	ND	FBE	N	54.93	120	Qc(wf), Qc(wc), Qgt(v), Qgdm(ec)	1	1	ND	82%
126	458	Keuler Field	-1.12	ND	48.22922	7.58	ND	FBE	N	61.32	115	Qgome	3	2	0	98%
127	459	Keuler Field	-0.49	ND	48.22353	7.66	ND	FBE	S	60.40	135	Qs?, Qgome	2	2	ND	98%
128	460	CGS Field	-0.04	101	48.03334	9.06	Bluff Crest	FBT	N	5.09	15	Oem(q), Qgt 100k	1	1	ND	94%
129	461	CGS Field	-0.06	55	47.92922	9.94	Bluff Toe	FB	N	12.92	80	Qga, Qgt 100k	4	2	ND	88%
130	462	CGS Field	-0.22	55	47.93028	9.97	Bluff Toe	FBE	N	12.88	105	Qga, Qgt 100k	4	2	ND	98%
131	463	CGS Field	-0.04	91	47.86830	10.53	Bluff Crest	TZ	S	4.57	12	Qgo 100k	4	1	0	39%
132	464	CGS Field	-0.14	54	47.68717	11.35	Bluff Toe	FB	S	7.73	100	Qb, Qgpc, Qgt 100k	2	1	ND	30%
133	465	CGS Field	-0.2	96	48.23822	11.52	Bluff Crest	FBE	S	7.36	60	Qgdme	3	2	0	46%
134	466	DSAS	-0.45	33	47.87782	10.33	Bluff Toe	FB	S	8.23	130	Qgt 100k	1	2	1	97%
135	467	DSAS	-0.68	25	48.07312	7.53	Bluff Crest	FB	S	6.07	80	Qgt v, Qguc (bluff face)	1	2	1	51%
136	468	DSAS	-0.17	57	48.08540	11.30	Log Line	FB	S	9.11	125	Qgome, Qgdv (bluff face)	3	4	0	25%
137	469	DSAS	-0.49	49	48.17828	11.43	Log Line	FB	S	10.06	90	Qgdme, Qgdf? (bluff face)	3	2	1	26%
138	470	DSAS	-0.36	28	47.89458	10.26	Bluff Crest	FB	S	9.62	90	Qgu 100k	3	3	1	46%
139	471	DSAS	-0.17	52	48.05622	11.23	Bluff Toe	FBE	S	8.46	180	Qgasv, Qguc (bluff face)	4	4	1	76%
140	472	DSAS	-0.53	52	48.05541	11.21	Bluff Toe	FBE	S	8.46	360	Qgtv, Qls/Qguc (bluff face)	1	4	ND	99%
141	473	DSAS	-0.14	36	47.64668	11.45	Bluff Toe	FB	S	8.42	105	Qgic, Qpu (bluff face)	3	1	ND	37%
142	474	DSAS	-0.44	45	48.29640	11.18	Bluff Crest	FBE	S	7.26	130	Qgdm ed, Qgics e, Qgtv, Qc o	3	3	1	82%
143	475	DSAS	-1.63	36	47.87146	10.67	Bluff Crest	FB	S	11.09	130	Qgt 100k	1	3	1	60%
144	476	DSAS	-0.40	36	47.97268	10.12	Bluff Crest	FBE	S	13.30	70	Qguc/Qgdme, Qgd d (bluff face)	4	3	1	81%
145	477	DSAS	-0.24	44	47.91343	10.71	Bluff Crest	FB	S	17.56	310	Qc w, Qgt (inland)	3	3	ND	96%
146	478	DSAS	-0.75	43	47.92620	10.61	Bluff Crest	FBE	S	18.12	290	Qgt	1	3	ND	80%
147	479	DSAS	-0.17	36	48.05156	7.83	Bluff Crest	FB	N	3.60	115	Qgome	3	3	ND	64%
148	480	DSAS	-0.16	44	48.06753	8.66	Bluff Toe	FB	S	2.38	20	Qgt 100k	1	4	ND	57%
149	481	DSAS	-0.49	35	47.66370	11.36	Bluff Crest	FB	N	6.44	250	Qga, Qls (bluff) 100k	4	3	1	77%

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150	482	DSAS	-0.14	32	48.14537	11.22	Bluff Crest	FB	S	6.36	220	Qgdme, Qgas v (bluff)	3	4	0	34%
151	483	DSAS	-0.17	44	48.06246	8.66	Bluff Crest	FB	S	2.16	20	Qga 100k	4	4	ND	72%
152	484	DSAS	-0.50	37	48.70747	8.51	Bluff Crest	FB	S	11.12	240	Qgd 100k	3	3	ND	59%
153	485	DSAS	-0.77	36	48.70654	8.64	Bluff Crest	FB	S	13.48	25	Qgd 100k	3	3	ND	20%
154	486	DSAS	-0.26	36	48.71024	8.64	Bluff Crest	FB	N	2.43	110	Qgd 100k	3	3	ND	29%
155	487	DSAS	-0.34	37	48.65048	8.46	Bluff Toe	FB	S	8.70	50	Qgome 100k	3	4	ND	78%
156	488	DSAS	-1.15	37	48.80052	8.92	Bluff Crest	FB	S	5.50	60	Qgomee 100k	3	3	ND	97%
157	490	DSAS	-0.27	80	47.45770	11.68	Bluff Crest	FB	S	2.54	100	Qvt, Qpog c, Qpon, Qpog f,	3	3	1	9%
158	491	DSAS	0.03	80	47.44376	11.72	Bluff Crest	FB	S	4.69	160	Qvt, Qpo, Qpog f	3	3	1	42%
159	492	DSAS	-0.25	80	47.38416	11.99	Bluff Crest	FB	S	2.28	60	Qgt 100k	1	1	ND	11%
160	493	DSAS	-0.13	80	47.37865	11.94	Bluff Crest	FB	S	1.92	115	Qga, Qc 100k	4	3	ND	80%
161	494	DSAS	-0.06	80	47.37472	11.95	Bluff Crest	FB	S	1.66	150	Qga, Qc 100k	4	3	ND	98%
162	495	DSAS	-0.36	32	48.39727	10.61	Bluff Crest	FB	N	3.01	80	Qgt v	1	4	1	47%
163	496	DSAS	-0.31	37	48.88409	9.11	Bluff Crest	FB	N	33.49	85	Qgdme 100k	3	4	ND	97%
164	497	DSAS	-0.23	80	47.42534	11.68	Bluff Crest	FB	N	11.75	90	Qgt	1	4	ND	19%
165	498	DSAS	-0.71	36	48.74645	8.82	Bluff Crest	FB	N	56.33	80	Qgomee 100k	3	3	ND	86%
166	499	DSAS	-0.28	33	47.88203	10.31	Bluff Toe	FB	S	3.41	190	Qgt	1	2	ND	60%
167	500	CGS	-0.18	39	48.53145	7.84	Bluff Crest	FB	S	7.42	70	Ji f 100k	4	4	0	0%
168	501	DSAS	-0.21	33	47.28724	14.04	Bluff Crest	FB	S	7.31	65	Qgt, Qu	1	1	1	54%
169	502	DSAS	-0.11	23	47.50459	11.40	Bluff Toe	FB	S	6.35	300	Qguc 1	4	4	1	32%
170	503	DSAS	-0.11	32	47.50076	11.40	Bluff Toe	FB	S	6.39	225	Qguc 1	4	4	1	37%
171	504	DSAS	-0.28	34	47.31325	14.09	Bluff Toe	FB	S	5.07	125	Qgt	1	2	1	82%
172	505	DSAS	-0.67	33	47.19436	14.12	Bluff Crest	FB	S	5.03	160	Qgt, Qu	2	4	0	52%
173	506	DSAS	-0.35	33	47.34569	14.12	Bluff Toe	FBE	S	6.82	110	Qgt	1	2	1	97%
174	507	DSAS	-0.14	34	47.36740	13.21	Bluff Crest	FB	S	8.19	100	Qgt, Qu	1	2	1	71%
175	508	DSAS	-0.25	35	47.15266	14.04	Bluff Crest	FB	N	6.54	65	Qgof, Qpg	2	2	1	17%
176	509	DSAS	-0.47	34	47.28015	12.52	Bluff Crest	FB	S	5.92	120	Qgt, Qgpc (bluff face) 100k	1	2	0	17%
177	510	DSAS	-0.27	34	47.25656	14.01	Bluff Crest	FBE	S	6.90	100	Qgt, Qga	4	4	0	94%
178	511	DSAS	-0.11	24	47.32171	14.08	Bluff Crest	TZ	S	1.66	60	Qgt	1	4	0	70%
179	512	CGS Field	-0.13	65	48.22735	11.52	Bluff Crest	FB	N	8.67	10	Qgog e	3	1	0	45%
180	513	DSAS	-0.14	44	48.17037	11.42	Bluff Toe	TZ	S	11.01	195	Qgt(v), Qmw	1	4	ND	30%
181	514	DSAS	-0.01	49	48.53895	7.64	Bluff Toe	TZ	N	5.93	100	Qvt, Qva	1	4	0	61%
182	515	Keuler Thesis	-0.34	39	48.57561	8.12	ND	FB	S	24.76	40	Qgom(e), Qgt (100k)	1	1	0	ND
183	516	Keuler Thesis	-0.10	50	48.53255	8.18	ND	FB	S	7.03	20	Qgdm(e) (100k)	4	4	0	ND
184	517	Keuler Thesis	-0.31	13	48.51907	8.17	ND (not used in	TZ	N	8.31	0	Qgdm(e), Qf (100k)	4	4	0	
185	518	Keuler Thesis	-0.20	91	48.48722	8.32	ND	FB	N	6.02	40	Qgdm(e)	1	1	0	ND
186	519	Keuler Thesis	-0.29	28	48.42703	10.57	ND	TZ	S	2.60	40	Qgt(v)	1	1	0	ND